The Origin of the Universe

Can you hear me?

According to the Boshongo people of central Africa, in the beginning, there was only darkness, water, and the great god Bumba. One day Bumba, in pain from a stomach ache, vomited up the sun. The sun dried up some of the water, leaving land. Still in pain, Bumba vomited up the moon, the stars, and then some animals. The leopard, the crocodile, the turtle, and finally, man.

This creation myth, like many others, tries to answer the questions we all ask. Why are we here? Where did we come from? The answer generally given was that humans were of comparatively recent origin, because it must have been obvious, even at early times, that the human race was improving in knowledge and technology. So it can't have been around that long, or it would have progressed even more. For example, according to Bishop Usher, the Book of Genesis placed the creation of the world at 9 in the morning on October the 27th, 4,004 BC. On the other hand, the physical surroundings, like mountains and rivers, change very little in a human lifetime. They were therefore thought to be a constant background, and either to have existed forever as an empty landscape, or to have been created at the same time as the humans. Not everyone, however, was happy with the idea that the universe had a beginning.

For example, Aristotle, the most famous of the Greek philosophers, believed the universe had existed forever. Something eternal is more perfect than something created. He suggested the reason we see progress was that floods, or other natural disasters, had repeatedly set civilization back to the beginning. The motivation for believing in an eternal universe was the desire to avoid invoking divine intervention to create the universe and set it going. Conversely, those who believed the universe had a beginning, used it as an argument for the existence of God as the first cause, or prime mover, of the universe.

If one believed that the universe had a beginning, the obvious question was what happened before the beginning? What was God doing before He made the world? Was He preparing Hell for people who asked such questions? The problem of whether or not the universe had a beginning was a great concern to the German philosopher, Immanuel Kant. He felt there were logical contradictions, or antimonies, either way. If the universe had a beginning, why did it wait an infinite time before it began? He called that the thesis. On the other hand, if the universe had existed for ever, why did it take an infinite time to reach the present stage? He called that the antithesis. Both the thesis and the antithesis depended on Kant's assumption, along with almost everyone else, that time was Absolute. That is to say, it went from the infinite past to the infinite future, independently of any universe that might or might not exist in this background. This is still the picture in the mind of many scientists today.

However in 1915, Einstein introduced his revolutionary General Theory of Relativity. In this, space and time were no longer Absolute, no longer a fixed background to events. Instead, they were dynamical quantities that were shaped by the matter and energy in the universe. They were defined only within the universe, so it made no sense to talk of a time before the universe began. It would be like asking for a point south of the South Pole. It is not defined. If the universe was essentially unchanging in time, as was generally assumed before the 1920s, there would be no reason that time should not be defined arbitrarily far back. Any so-called beginning of the universe would be artificial, in the sense that one could extend the history back to earlier times. Thus it might be that the universe was created last year, but with all the memories and physical evidence, to look like it was much older. This raises deep philosophical questions about the meaning of existence. I shall deal with these by adopting what is called, the positivist approach. In this, the idea is that we interpret the input from our senses in terms of a model we make of the world. One cannot ask whether the model represents reality, only whether it works. A model is a good model if first it interprets a wide range of observations, in terms of a simple and elegant model. And second, if the model makes definite predictions that can be tested and possibly falsified by observation.

In terms of the positivist approach, one can compare two models of the universe. One in which the universe was created last year and one in which the universe existed much longer. The Model in which the universe existed for longer than a year can explain things like identical twins that have a common cause more than a year ago. On the other hand, the model in which the universe was created last year cannot explain such events. So the first model is better. One cannot ask whether the universe really existed before a year ago or just appeared to. In the positivist approach, they are the same. In an unchanging universe, there would be no natural starting point. The situation changed radically however, when Edwin Hubble began to make observations with the hundred inch telescope on Mount Wilson, in the 1920s.

Hubble found that stars are not uniformly distributed throughout space, but are gathered together in vast collections called galaxies. By measuring the light from galaxies, Hubble could determine their velocities. He was expecting that as many galaxies would be moving towards us as were moving away. This is what one would have in a universe that was unchanging with time. But to his surprise, Hubble found that nearly all the galaxies were moving away from us. Moreover, the further galaxies were from us, the faster they were moving away. The universe was not unchanging with time as everyone had thought previously. It was expanding. The distance between distant galaxies was increasing with time.

The expansion of the universe was one of the most important intellectual discoveries of the 20th century, or of any century. It transformed the debate about whether the universe had a beginning. If galaxies are moving apart now, they must have been closer together in the past. If their speed had been constant, they would all have been on top of one another about 15 billion years ago. Was this the beginning of the universe? Many scientists were still unhappy with the universe having a beginning because it seemed to imply that physics broke down. One would have to invoke an outside agency, which for convenience, one can call God, to determine how the universe began. They therefore advanced theories in which the universe was expanding at the present time, but didn't have a beginning. One was the Steady State theory, proposed by Bondi, Gold, and Hoyle in 1948.

In the Steady State theory, as galaxies moved apart, the idea was that new galaxies would form from matter that was supposed to be continually being created throughout space. The universe would have existed for ever and would have looked the same at all times. This last property had the great virtue, from a positivist point of view, of being a definite prediction that could be tested by observation. The Cambridge radio astronomy group, under Martin Ryle, did a survey of weak radio sources in the early 1960s. These were distributed fairly uniformly across the sky, indicating that most of the sources lay outside our galaxy. The weaker sources would be further away, on average. The Steady State theory predicted the shape of the graph of the number of sources against source strength. But the observations showed more faint sources than predicted, indicating that the density sources were higher in the past. This was contrary to the basic assumption of the Steady State theory, that everything was constant in time. For this, and other reasons, the Steady State theory was abandoned.

Another attempt to avoid the universe having a beginning was the suggestion that there was a previous contracting phase, but because of rotation and local irregularities, the matter would not all fall to the same point. Instead, different parts of the matter would miss each other, and the universe would expand again with the density remaining finite. Two Russians, Lifshitz and Khalatnikov, actually claimed to have proved, that a general contraction without exact symmetry would always lead to a bounce with the density remaining finite. This result was very convenient for Marxist Leninist dialectical materialism, because it avoided awkward questions about the creation of the universe. It therefore became an article of faith for Soviet scientists.

When Lifshitz and Khalatnikov published their claim, I was a 21 year old research student looking for something to complete my PhD thesis. I didn't believe their so-called proof, and set out with Roger Penrose to develop new mathematical techniques to study the question. We showed that the universe couldn't bounce. If Einstein's General Theory of Relativity is correct, there will be a singularity, a point of infinite density and spacetime curvature, where time has a beginning. Observational evidence to confirm the idea that the universe had a very dense beginning came in October 1965, a few months after my first singularity result, with the discovery of a faint background of microwaves throughout space. These microwaves are the same as those in your microwave oven, but very much less powerful. They would heat your pizza only to minus 271 point 3 degrees centigrade, not much good for defrosting the pizza, let alone cooking it. You can actually observe these microwaves yourself. Set your television to an empty channel. A few percent of the snow you see on the screen will be caused by this background of microwaves. The only reasonable interpretation of the background is that it is radiation left over from an early very hot and dense state. As the universe expanded, the radiation would have cooled until it is just the faint remnant we observe today.

Although the singularity theorems of Penrose and myself, predicted that the universe had a beginning, they didn't say how it had begun. The equations of General Relativity would break down at the singularity. Thus Einstein's theory cannot predict how the universe will begin, but only how it will evolve once it has begun. There are two attitudes one can take to the results of Penrose and myself. One is to that God chose how the universe began for reasons we could not understand. This was the view of Pope John Paul. At a conference on cosmology in the Vatican, the Pope told the delegates that it was OK to study the universe after it began, but they should not inquire into the beginning itself, because that was the moment of creation, and the work of God. I was glad he didn't realize I had presented a paper at the conference suggesting how the universe began. I didn't fancy the thought of being handed over to the Inquisition, like Galileo.

The other interpretation of our results, which is favored by most scientists, is that it indicates that the General Theory of Relativity breaks down in the very strong gravitational fields in the early universe. It has to be replaced by a more complete theory. One would expect this anyway, because General Relativity does not take account of the small scale structure of matter, which is governed by quantum theory. This does not matter normally, because the scale of the universe is enormous compared to the microscopic scales of quantum theory. But when the universe is the Planck size, a billion trillion trillionth of a centimeter, the two scales are the same, and quantum theory has to be taken into account.

In order to understand the Origin of the universe, we need to combine the General Theory of Relativity with quantum theory. The best way of doing so seems to be to use Feynman's idea of a sum over histories. Richard Feynman was a colorful character, who played the bongo drums in a strip joint in Pasadena, and was a brilliant physicist at the California Institute of Technology. He proposed that a system got from a state A, to a state B, by every possible path or history. Each path or history has a certain amplitude or intensity, and the probability of the system going from A- to B, is given by adding up the amplitudes for each path. There will be a history in which the moon is made of blue cheese, but the amplitude is low, which is bad news for mice.

The probability for a state of the universe at the present time is given by adding up the amplitudes for all the histories that end with that state. But how did the histories start? This is the Origin question in another guise. Does it require a Creator to decree how the universe began? Or is the initial state of the universe, determined by a law of science? In fact, this question would arise even if the histories of the universe went back to the infinite past. But it is more immediate if the universe began only 15 billion years ago. The problem of what happens at the beginning of time is a bit like the question of what happened at the edge of the world, when people thought the world was flat. Is the world a flat plate with the sea pouring over the edge? I have tested this experimentally. I have been round the world, and I have not fallen off. As we all know, the problem of what happens at the edge of the world was solved when people realized that the world was not a flat plate, but a curved surface. Time however, seemed to be different. It appeared to be separate from space, and to be like a model railway track. If it had a beginning, there would have to be someone to set the trains going. Einstein's General Theory of Relativity unified time and space as spacetime, but time was still different from space and was like a corridor, which either had a beginning and end, or went on forever. However, when one combines General Relativity with Quantum Theory, Jim Hartle and I realized that time can behave like another direction in space under extreme conditions. This means one can get rid of the problem of time having a beginning, in a similar way in which we got rid of the edge of the world. Suppose the beginning of the universe was like the South Pole of the earth, with degrees of latitude playing the role of time. The universe would start as a point at the South Pole. As one moves north, the circles of constant latitude, representing the size of the universe, would expand. To ask what happened before the beginning of the universe would become a meaningless question, because there is nothing south of the South Pole.

Time, as measured in degrees of latitude, would have a beginning at the South Pole, but the South Pole is much like any other point, at least so I have been told. I have been to Antarctica, but not to the South Pole. The same laws of Nature hold at the South Pole as in other places. This would remove the age-old objection to the universe having a beginning; that it would be a place where the normal laws broke down. The beginning of the universe would be governed by the laws of science. The picture Jim Hartle and I developed of the spontaneous quantum creation of the universe would be a bit like the formation of bubbles of steam in boiling water.

The idea is that the most probable histories of the universe would be like the surfaces of the bubbles. Many small bubbles would appear, and then disappear again. These would correspond to mini universes that would expand but would collapse again while still of microscopic size. They are possible alternative universes but they are not of much interest since they do not last long enough to develop galaxies and stars, let alone intelligent life. A few of the little bubbles, however, grow to a certain size at which they are safe from recollapse. They will continue to expand at an ever increasing rate, and will form the bubbles we see. They will correspond to universes that would start off expanding at an ever increasing rate. This is called inflation, like the way prices go up every year.

The world record for inflation was in Germany after the First World War. Prices rose by a factor of ten million in a period of 18 months. But that was nothing compared to inflation in the early universe. The universe expanded by a factor of million trillion trillion in a tiny fraction of a second. Unlike inflation in prices, inflation in the early universe was a very good thing. It produced a very large and uniform universe, just as we observe. However, it would not be completely uniform. In the sum over histories, histories that are very slightly irregular will have almost as high probabilities as the completely uniform and regular history. The theory therefore predicts that the early universe is likely to be slightly non-uniform. These irregularities would produce small variations in the intensity of the microwave background from different directions. The microwave background has been observed by the Map satellite, and was found to have exactly the kind of variations predicted. So we know we are on the right lines.

The irregularities in the early universe will mean that some regions will have slightly higher density than others. The gravitational attraction of the extra density will slow the expansion of the region, and can eventually cause the region to collapse to form galaxies and stars. So look well at the map of the microwave sky. It is the blue print for all the structure in the universe. We are the product of quantum fluctuations in the very early universe. God really does play dice.

We have made tremendous progress in cosmology in the last hundred years. The General Theory of Relativity and the discovery of the expansion of the universe shattered the old picture of an ever existing and ever lasting universe. Instead, general relativity predicted that the universe, and time itself, would begin in the big bang. It also predicted that time would come to an end in black holes. The discovery of the cosmic microwave background and observations of black holes support these conclusions. This is a profound change in our picture of the universe and of reality itself. Although the General Theory of Relativity predicted that the universe must have come from a period of high curvature in the past, it could not predict how the universe would emerge from the big bang. Thus general relativity on its own cannot answer the central question in cosmology: Why is the universe the way it is? However, if general relativity is combined with quantum theory, it may be possible to predict how the universe would start. It would initially expand at an ever increasing rate.

During this so called inflationary period, the marriage of the two theories predicted that small fluctuations would develop and lead to the formation of galaxies, stars, and all the other structure in the universe. This is confirmed by observations of small non uniformities in the cosmic microwave background, with exactly the predicted properties. So it seems we are on our way to understanding the origin of the universe, though much more work will be needed. A new window on the very early universe will be opened when we can detect gravitational waves by accurately measuring the distances between space craft. Gravitational waves propagate freely to us from earliest times, unimpeded by any intervening material. By contrast, light is scattered many times by free electrons. The scattering goes on until the electrons freeze out, after 300,000 years.

Despite having had some great successes, not everything is solved. We do not yet have a good theoretical understanding of the observations that the expansion of the universe is accelerating again, after a long period of slowing down. Without such an understanding, we cannot be sure of the future of the universe. Will it continue to expand forever? Is inflation a law of Nature? Or will the universe eventually collapse again? New observational results and theoretical advances are coming in rapidly. Cosmology is a very exciting and active subject. We are getting close to answering the age old questions. Why are we here? Where did we come from?

Thank you for listening to me.

Into a Black Hole

Can you hear me?

It is a great pleasure for me to be back again in Chile, to celebrate the sixtieth birthday of an old friend, and esteemed colleague, Claudio Bunster, whom I have known for almost forty years. Claudio has done so much for science in general, and for science in Chile in particular. Being in the city of Valdivia where CECs, the center he created, is located, is quite meaningful to me.

It is said that fact is sometimes stranger than fiction, and nowhere is this more true than in the case of black holes. Black holes are stranger than anything dreamt up by science fiction writers, but they are firmly matters of science ~fact. Not that science fiction was slow to climb on the band-wagon after black holes were discovered.. I remember going to the premier of a Walt Dizny film, The Black Hole, in the 1970s. It was about a spaceship, that was sent to investigate a black hole that had been discovered. It wasn't a very good film, but it had an interesting ending. After orbiting the black hole, one of the scientists decides, the only way to find out what is going on, is to go inside. So he gets into a space probe, and dives into the black hole. After a screen writer's depiction of Hell, he emerges into a new universe. This is an early example of the science fiction use of a black hole as a wormhole, a passage from one universe to another, or back to another location in the same universe. Such wormholes, if they existed, would provide short cuts for Interstellar space travel, which otherwise would be pretty slow and tedious, if one had to keep to the Einstein speed limit, and stay below the speed of light.

In fact, science fiction writers should not have been taken so much by surprise. The idea behind black holes, has been around in the scientific community for more than 200 years. In 1783,a Cambridge don, John Michell, wrote a paper in the Philosophical Transactions of the Royal Society of London,about what he called dark stars. He pointed out that a star that was sufficiently massive and compact, would have such a strong gravitational field that light could not escape. Any light emitted from the surface of the star, would be dragged back by the star's gravitational attraction, before it could get very far. Michell suggested that there might be a large number of stars like this. Although we would not be able to see them, because the light from them would not reach us, we would still feel their gravitational attraction. Such objects are what we now call black holes, because that is what they are, black voids in space. A similar suggestion was made a few years later, by the French scientist the Marquis de La~plass, apparently independently of Michell. Interestingly enough, La~plass included it in only the first and second editions of his book, The System of the World, and left it out of later editions. Perhaps he decided that it was a crazy idea.

Both Michell and La~plass thought of light as consisting of particles, rather like cannon balls, that could be slowed down by gravity, and made to fall back on the star. But a famous experiment, carried out by two Americans, Michelson and Morley in 1887, showed that light always traveled at a speed of one hundred and eighty six thousand miles a second, no matter where it came from. How then could gravity slow down light, and make it fall back. This was impossible, according to the then accepted ideas of space and time. But in 1915, Einstein put forward his revolutionary General Theory of Relativity. In this, space and time were no longer separate and independent entities. Instead, they were just different directions in a single object called spacetime. This spacetime was not flat, but was warped and curved by the matter and energy in it. In order to understand this, considered a sheet of rubber, with a weight placed on it, to represent a star. The weight will form a depression in the rubber, and will cause the sheet near the star to be curved, rather than flat. If one now rolls marbles on the rubber sheet, their paths will be curved, rather than being straight lines. In 1919, a British expedition to West Africa, looked at light from distant stars, that passed near the Sun during an eclipse. They found that the images of the stars, were shifted slightly from their normal positions. This indicated that the paths of the light from the stars, had been bent by the curved spacetime near the Sun. General Relativity was confirmed.

Consider now placing heavier and heavier, and more and more concentrated weights on the rubber sheet. They will depress the sheet more and more. Eventually, at a critical weight and size, they will make a bottomless hole in the sheet, that particles can fall into, but nothing can get out of.

What happens in spacetime according to General Relativity, is rather similar. A star will curve and distort the spacetime near it, more and more, the more massive and more compact the star is. If a massive star that has burnt up its nuclear fuel, cools and shrinks below a critical size, it will quite literally make a bottomless hole in spacetime, that light can't get out of. Such objects were given the name, black holes, by the American physicist, John Wheeler, who was one of the first to recognize their importance, and the problems they pose. The name caught on quickly.It suggested something dark and mysterious, But the French, being French, saw a more riskay meaning. For years, they resisted the name, troo noir, claiming it was obscene. But that was a bit like trying to stand against ~le week end, and other franglay. In the end, they had to give in.Who can resist a name that is such a winner.

From the outside, you can't tell what is inside a black hole. You can throw television sets, diamond rings, or even your worst enemies into a black hole, and all the black hole will remember, is the total mass, and the state of rotation. John Wheeler called this, A Black Hole Has No Hair. To the French, this just confirmed their suspicions.

A black hole has a boundary, called the event horizon. It is where gravity is just strong enough to drag light back, and prevent it escaping. Because nothing can travel faster than light, everything else will get dragged back also. Falling through the event horizon, is a bit like going over Niagra Falls in a canoe. If you are above the falls, you can get away if you paddle fast enough, but once you are over the edge, you are lost.There's no way back. As you get nearer the falls, the current gets faster. This means it pulls harder on the front of the canoe, than the back. there's a danger that the canoe will be pulled apart. It is the same with black holes. If you fall towards a black hole feet first, gravity will pull harder on your feet than your head, because they are nearer the black hole. The result is, you will be stretched out longwise, and squashed in sideways.. If the black hole has a mass of a few times our sun, you would be torn apart, and made into spaghetti, before you reached the horizon. However, if you fell into a much larger black hole, with a mass of a million times the sun, you would reach the horizon without difficulty. So, if you want to explore the inside of a black hole, choose a big one. There is a black hole of about a million solar masses, at the center of our Milky way galaxy.

Although you wouldn't notice anything particular as you fell into a black hole, someone watching you from a distance, would never see you cross the event horizon. Instead, you would appear to slow down, and hover just outside. You would get dimmer and dimmer, and redder and redder, until you were effectively lost from sight. As far as the outside world is concerned, you would be lost for ever. Because black holes have no hair, in Wheeler's phrase, one can't tell from the outside what is inside a black hole, apart from its mass and rotation. This means that a black hole contains a lot of information that is hidden from the outside world. But there's a limit to the amount of information, one can pack into a region of space. Information requires energy, and energy has mass, by Einstein's famous equation, E = m c squared. So if there's too much information in a region of space, it will collapse into a black hole, and the size of the black hole will reflect the amount of information. It is like piling more and more books into a library. Eventually, the shelves will give way, and the library will collapse into a black hole.

If the amount of hidden information inside a black hole, depends on the size of the hole, one would expect from general principles, that the black hole would have a temperature, and would glow like a piece of hot metal. But that was impossible, because as everyone knew, nothing could get out of a black hole. Or so it was thought, but I discovered that particles can leak out of a black hole. The reason is, that on a very small scale, things are a bit fuzzy. This is summed up in the uncertainty relation, discovered by Werner Heisenberg in 1923, which says that the more precisely you know the position of a particle, the less precisely you can know its speed, and vice versa. This means that if a particle is in a small black hole, you know its position fairly accurately. Its speed therefore will be rather uncertain, and can be more than the peed of light, which would allow the particle to escape from the black hole. The larger the black hole, the less accurately the position of a particle in it is defined, so the more precisely the speed is defined, and the less chance there is that it will be more than the speed of light,. A black hole of the mass of the sun, would leak particles at such a slow rate, it would be impossible to detect. However, there could be much smaller mini black holes. These might have formed in the very early universe, if it had been chaotic and irregular. A black hole of the mass of a mountain, would give off x-rays and gamma rays, at a rate of about ten million Megawatts, enough to power the world's electricity supply. It wouldn't be easy however, to harnass a mini black hole. You couldn't keep it in a power station, because it would drop through the floor, and end up at the center of the Earth. About the only way, would be to have the black hole in orbit around the Earth.

People have searched for mini black holes of this mass, but have so far, not found any. This is a pity, because if they had, I would have got a Nobel prize. Another possibility however, is that we might be able to create micro black holes in the extra dimensions of space time. According to some theories, the universe we experience, is just a four dimensional surface, in a ten or eleven dimensional space. We wouldn't see these extra dimensions, because light wouldn't propagate through them, but only through the four dimensions of our universe. Gravity, however, would affect the extra dimensions, and would be much stronger than in our universe. This would make it much easier to form a little black hole in the extra dimensions. It might be possible to observe this at the LHC, the Large Hadron Collider, at Cern, in Switzerland. This consists of a circular tunnel, 27 kilometers long.Two beams of particles travel round this tunnel in opposite directions, and are made to collide. Some of the collisions might create micro black holes. These would radiate particles in a pattern that would be easy to recognize. So, I might get a Nobel prize, after all.

As particles escape from a black hole the hole will lose mass, and shrink.This will increase the rate of emission of particles. Eventually, the black hole will lose all its mass, and disappear. What then happens to all the particles and unlucky astronauts, that fell into the black hole. They can't just re-emerge when the black hole disappears. The particles that come out of a black hole, seem to be completely random, and to bear no relation to what fell in. It appears that the information about what fell in, is lost, apart from the total amount of mass, and the amount of rotation. But if information is lost, this raises a serious problem that strikes at the heart of our understanding of science. For more than 200 years, we have believed in Scientific determinism, that is, that the laws of science, determine the evolution of the universe. This was formulated by La~plass as, If we know the state of the universe at one time, the laws of science will determine it at all future and past times. Napoleon is said to have asked La~plass how God fitted into this picture. La~plass replied, Sire, I have not needed that hypothesis. I don't think that La~plass was claiming that God didn't exist. It is just that He doesn't intervene, to break the laws of Science. That must be the position of every scientist. A scientific law, is not a scientific law, if it only holds when some supernatural being, decides to let things run, and not intervene.

In La~plass's determinism, one needed to know the positions and speeds of all particles at one time in order to predict the future. But according to the uncertainty relation, the more accurately you know the positions, the less accurately you can know the speeds, and vice versa. In other words, you can't know ~both the positions, ~and the speeds, accurately. How then can you predict the future accurately? The answer is, that although one can't predict the positions and speeds separately, one ~can predict what is called, the quantum state. This is something from which both positions and speeds can be calculated, to a certain degree of accuracy. We would still expect the universe to be deterministic, in the sense that if we knew the quantum state of the universe at one time, the laws of science should enable us predict it at any other time.

If information were lost in black holes, we wouldn't be able to predict the future, because a black hole could emit any collection of particles. It could emit a working television set, or a leather bound volume of the complete works of Shakespeare, though the chance of such exotic emissions is very low. It is much more likely to be thermal Radiation, like the glow from red hot metal. It might seem that it wouldn't matter very much if we couldn't predict what comes out of black holes. There aren't any black holes near us. But it is a matter of principle. If determinism breaks down with black holes, it could break down in other situations. There could be virtual black holes that appear as fluctuations out of the vacuum, absorb one set of particles, emit another, and disappear into the vacuum again. Even worse, if determinism breaks down, we can't be sure of our past history either. The history books and our memories could just be illusions. It is the past that tells us who we are. Without it, we lose our identity.

It was therefore very important to determine whether information really was lost in black holes, or whether in principle, it could be recovered. Many people felt that information should not be lost, but no one could suggest a mechanism by which it could be preserved. The arguments went on for years. Finally, I found what I think is the answer. It depends on the idea of Richard Feinman, that there isn't a single history, but many different possible histories, each with their own probability. In this case, there are two kinds of history. In one, there is a black hole, into which particles can fall, but in the other kind, there is no black hole. The point is, that from the outside, one can't be certain whether there is a black hole, or not. So there is always a chance that there isn't a black hole. This possibility is enough to preserve the information, but the information is not returned in a very useful form. It is like burning an encyclopedia.. Information is not lost if you keep all the smoke and ashes, but it is difficult to read. Kip Thorne and I had a bet with John Preskill, that information would be lost in black holes. When I discovered how information could be preserved, I conceded the bet.I gave John Preskill an encyclopedia. Maybe I should have just given him the ashes.

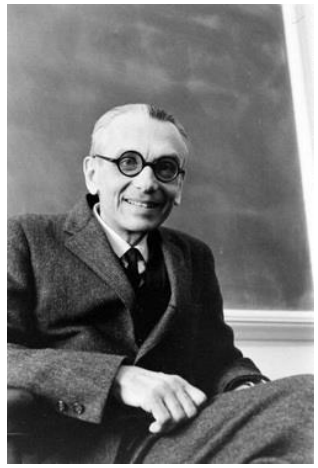
What does this tell us about whether it is possible to fall in a black hole, and come out in another universe. The existence of alternative histories with black holes, suggests this might be possible. The hole would need to be large, and if it was rotating, it might have a passage to another universe. But you couldn't come back to our universe. So, although I'm keen on space flight, I'm not going to try that.

The message of this lecture, is, that black holes ain't as black as they are painted. They are not the eternal prisons they were once thought. Things ~can get out of a black hole, both to the outside, and possibly, to another universe. So, if you feel you are in a black hole, don't give up. There's a way out.

I would like to thank the organizers of this meeting again, for inviting me, to this beautiful country, which I discovered about ten years ago. My stay in Chile is not over, and I look forward to the coming days.,

Thank you for listening.

Godel and the End of the Universe



In this talk, I want to ask how far can we go in our search for understanding and knowledge. Will we ever find a complete form of the laws of nature? By a complete form, I mean a set of rules that in principle at least enable us to predict the future to an arbitrary accuracy, knowing the state of the universe at one time. A qualitative understanding of the laws has been the aim of philosophers and scientists, from Aristotle onwards. But it was Newton's Principia Mathematica in 1687, containing his theory of universal gravitation that made the laws quantitative and precise. This led to the idea of scientific determinism, which seems first to have been expressed by Laplace. If at one time, one knew the positions and velocities of all the particles in the universe, the laws of science should enable us to calculate their positions and velocities at any other time, past or future. The laws may or may not have been ordained by God, but scientific determinism asserts that he does not intervene to break them.

At first, it seemed that these hopes for a complete determinism would be dashed by the discovery early in the 20th century; that events like the decay of radioactive atoms seemed to take place at random. It was as if God was playing dice, in Einstein's phrase. But science snatched victory from the jaws of defeat by moving the goal posts and redefining what is meant by a complete knowledge of the universe. It was a stroke of brilliance whose philosophical implications have still not been fully appreciated. Much of the credit belongs to Paul Dirac, my predecessor but one in the Lucasian chair, though it wasn't motorized in his time. Dirac showed how the work of Erwin Schrodinger and Werner Heisenberg could be combined in new picture of reality, called quantum theory. In quantum theory, a particle is not characterized by two quantities, its position and its velocity, as in classical Newtonian theory. Instead it is described by a single quantity, the wave function. The size of the wave function at a point, gives the probability that the particle will be found at that point, and the rate at which the wave function changes from point to point, gives the probability of different velocities. One can have a wave function that is sharply peaked at a point. This corresponds to a state in which there is little uncertainty in the position of the particle. However, the wave function varies rapidly, so there is a lot of uncertainty in the velocity. Similarly, a long chain of waves has a large uncertainty in position, but a small uncertainty in velocity. One can have a well defined position, or a well defined velocity, but not both.

This would seem to make complete determinism impossible. If one can't accurately define both the positions and the velocities of particles at one time, how can one predict what they will be in the future? It is like weather forecasting. The forecasters don't have an accurate knowledge of the atmosphere at one time. Just a few measurements at ground level and what can be learnt from satellite photographs. That’s why weather forecasts are so unreliable. However, in quantum theory, it turns out one doesn't need to know both the positions and the velocities. If one knew the laws of physics and the wave function at one time, then something called the Schrodinger equation would tell one how fast the wave function was changing with time. This would allow one to calculate the wave function at any other time. One can therefore claim that there is still determinism but it is determinism on a reduced level. Instead of being able accurately to predict two quantities, position and velocity, one can predict only a single quantity, the wave function. We have re-defined determinism to be just half of what Laplace thought it was. Some people have tried to connect the unpredictability of the other half with consciousness, or the intervention of supernatural beings. But it is difficult to make either case for something that is completely random.

In order to calculate how the wave function develops in time, one needs the quantum laws that govern the universe. So how well do we know these laws? As Dirac remarked, Maxwell's equations of light and the relativistic wave equation, which he was too modest to call the Dirac equation, govern most of physics and all of chemistry and biology. So in principle, we ought to be able to predict human behavior, though I can't say I have had much success myself. The trouble is that the human brain contains far too many particles for us to be able to solve the equations. But it is comforting to think we might be able to predict the nematode worm, even if we can't quite figure out humans. Quantum theory and the Maxwell and Dirac equations indeed govern much of our life, but there are two important areas beyond their scope. One is the nuclear forces. The other is gravity. The nuclear forces are responsible for the Sun shining and the formation of the elements including the carbon and oxygen of which we are made. And gravity caused the formation of stars and planets, and indeed, of the universe itself. So it is important to bring them into the scheme.

The so called weak nuclear forces have been unified with the Maxwell equations by Abdus Salam and Stephen Weinberg, in what is known as the Electro weak theory. The predictions of this theory have been confirmed by experiment and the authors rewarded with Nobel Prizes. The remaining nuclear forces, the so called strong forces, have not yet been successfully unified with the electro weak forces in an observationally tested scheme. Instead, they seem to be described by a similar but separate theory called QCD. It is not clear who, if anyone, should get a Nobel Prize for QCD, but David Gross and Gerard ‘t Hooft share credit for showing the theory gets simpler at high energies. I had quite a job to get my speech synthesizer to pronounce Gerard's surname. It wasn't familiar with apostrophe t. The electro weak theory and QCD together constitute the so called Standard Model of particle physics, which aims to describe everything except gravity.

The standard model seems to be adequate for all practical purposes, at least for the next hundred years. But practical or economic reasons have never been the driving force in our search for a complete theory of the universe. No one working on the basic theory, from Galileo onward, has carried out their research to make money, though Dirac would have made a fortune if he had patented the Dirac equation. He would have had a royalty on every television, walkman, video game and computer.

The real reason we are seeking a complete theory, is that we want to understand the universe and feel we are not just the victims of dark and mysterious forces. If we understand the universe, then we control it, in a sense. The standard model is clearly unsatisfactory in this respect. First of all, it is ugly and ad hoc. The particles are grouped in an apparently arbitrary way, and the standard model depends on 24 numbers whose values can not be deduced from first principles, but which have to be chosen to fit the observations. What understanding is there in that? Can it be Nature's last word? The second failing of the standard model is that it does not include gravity. Instead, gravity has to be described by Einstein's General Theory of Relativity. General relativity is not a quantum theory unlike the laws that govern everything else in the universe. Although it is not consistent to use the non quantum general relativity with the quantum standard model, this has no practical significance at the present stage of the universe because gravitational fields are so weak. However, in the very early universe, gravitational fields would have been much stronger and quantum gravity would have been significant. Indeed, we have evidence that quantum uncertainty in the early universe made some regions slightly more or less dense than the otherwise uniform background. We can see this in small differences in the background of microwave radiation from different directions. The hotter, denser regions will condense out of the expansion as galaxies, stars and planets. All the structures in the universe, including ourselves, can be traced back to quantum effects in the very early stages. It is therefore essential to have a fully consistent quantum theory of gravity, if we are to understand the universe.

Constructing a quantum theory of gravity has been the outstanding problem in theoretical physics for the last 30 years. It is much, much more difficult than the quantum theories of the strong and electro weak forces. These propagate in a fixed background of space and time. One can define the wave function and use the Schrodinger equation to evolve it in time. But according to general relativity, gravity is space and time. So how can the wave function for gravity evolve in time? And anyway, what does one mean by the wave function for gravity? It turns out that, in a formal sense, one can define a wave function and a Schrodinger like equation for gravity, but that they are of little use in actual calculations.

Instead, the usual approach is to regard the quantum spacetime as a small perturbation of some background spacetime; generally flat space. The perturbations can then be treated as quantum fields, like the electro weak and QCD fields, propagating through the background spacetime. In calculations of perturbations, there is generally some quantity called the effective coupling which measures how much of an extra perturbation a given perturbation generates. If the coupling is small, a small perturbation creates a smaller correction which gives an even smaller second correction, and so on. Perturbation theory works and can be used to calculate to any degree of accuracy. An example is your bank account. The interest on the account is a small perturbation. A very small perturbation if you are with one of the big banks. The interest is compound. That is, there is interest on the interest, and interest on the interest on the interest. However, the amounts are tiny. To a good approximation, the money in your account is what you put there. On the other hand, if the coupling is high, a perturbation generates a larger perturbation which then generates an even larger perturbation. An example would be borrowing money from loan sharks. The interest can be more than you borrowed, and then you pay interest on that. It is disastrous.

With gravity, the effective coupling is the energy or mass of the perturbation because this determines how much it warps spacetime, and so creates a further perturbation. However, in quantum theory, quantities like the electric field or the geometry of spacetime don't have definite values, but have what are called quantum fluctuations. These fluctuations have energy. In fact, they have an infinite amount of energy because there are fluctuations on all length scales, no matter how small. Thus treating quantum gravity as a perturbation of flat space doesn't work well because the perturbations are strongly coupled.

Supergravity was invented in 1976 to solve, or at least improve, the energy problem. It is a combination of general relativity with other fields, such that each species of particle has a super partner species. The energy of the quantum fluctuations of one partner is positive, and the other negative, so they tend to cancel. It was hoped the infinite positive and negative energies would cancel completely, leaving only a finite remainder. In this case, a perturbation treatment would work because the effective coupling would be weak. However, in 1985, people suddenly lost confidence that the infinities would cancel. This was not because anyone had shown that they definitely didn't cancel. It was reckoned it would take a good graduate student 300 years to do the calculation, and how would one know they hadn't made a mistake on page two? Rather it was because Ed Witten declared that string theory was the true quantum theory of gravity, and supergravity was just an approximation, valid when particle energies are low, which in practice, they always are. In string theory, gravity is not thought of as the warping of spacetime. Instead, it is given by string diagrams; networks of pipes that represent little loops of string, propagating through flat spacetime. The effective coupling that gives the strength of the junctions where three pipes meet is not the energy, as it is in supergravity. Instead it is given by what is called the dilaton; a field that has not been observed. If the dilaton had a low value, the effective coupling would be weak, and string theory would be a good quantum theory. But it is no earthly use for practical purposes.

In the years since 1985, we have realized that both supergravity and string theory belong to a larger structure, known as M theory. Why it should be called M Theory is completely obscure. M theory is not a theory in the usual sense. Rather it is a collection of theories that look very different but which describe the same physical situation. These theories are related by mappings or correspondences called dualities, which imply that they are all reflections of the same underlying theory. Each theory in the collection works well in the limit, like low energy, or low dilaton, in which its effective coupling is small, but breaks down when the coupling is large. This means that none of the theories can predict the future of the universe to arbitrary accuracy. For that, one would need a single formulation of M-theory that would work in all situations.

Up to now, most people have implicitly assumed that there is an ultimate theory that we will eventually discover. Indeed, I myself have suggested we might find it quite soon. However, M-theory has made me wonder if this is true. Maybe it is not possible to formulate the theory of the universe in a finite number of statements. This is very reminiscent of Godel's theorem. This says that any finite system of axioms is not sufficient to prove every result in mathematics.

Godel's theorem is proved using statements that refer to themselves. Such statements can lead to paradoxes. An example is, this statement is false. If the statement is true, it is false. And if the statement is false, it is true. Another example is, the barber of Corfu shaves every man who does not shave himself. Who shaves the barber? If he shaves himself, then he doesn't, and if he doesn't, then he does. Godel went to great lengths to avoid such paradoxes by carefully distinguishing between mathematics, like 2+2 =4, and meta mathematics, or statements about mathematics, such as mathematics is cool, or mathematics is consistent. That is why his paper is so difficult to read. But the idea is quite simple. First Godel showed that each mathematical formula, like 2+2=4, can be given a unique number, the Godel number. The Godel number of 2+2=4, is *. Second, the meta mathematical statement, the sequence of formulas A, is a proof of the formula B, can be expressed as an arithmetical relation between the Godel numbers for A- and B. Thus meta mathematics can be mapped into arithmetic, though I'm not sure how you translate the meta mathematical statement, 'mathematics is cool'. Third and last, consider the self referring Godel statement, G. This is, the statement G cannot be demonstrated from the axioms of mathematics. Suppose that G could be demonstrated. Then the axioms must be inconsistent because one could both demonstrate G and show that it cannot be demonstrated. On the other hand, if G can't be demonstrated, then G is true. By the mapping into numbers, it corresponds to a true relation between numbers, but one which can not be deduced from the axioms. Thus mathematics is either inconsistent or incomplete. The smart money is on incomplete.

What is the relation between Godel's theorem and whether we can formulate the theory of the universe in terms of a finite number of principles? One connection is obvious. According to the positivist philosophy of science, a physical theory is a mathematical model. So if there are mathematical results that cannot be proved, there are physical problems that cannot be predicted. One example might be the Goldbach conjecture. Given an even number of wood blocks, can you always divide them into two piles, each of which cannot be arranged in a rectangle? That is, it contains a prime number of blocks.

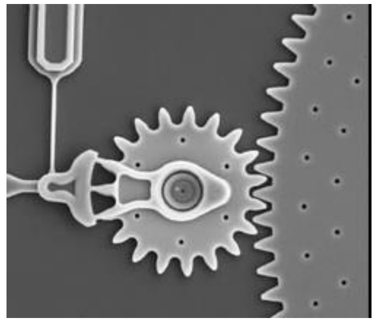
Although this is incompleteness of sort, it is not the kind of unpredictability I mean. Given a specific number of blocks, one can determine with a finite number of trials whether they can be divided into two primes. But I think that quantum theory and gravity together, introduces a new element into the discussion that wasn't present with classical Newtonian theory. In the standard positivist approach to the philosophy of science, physical theories live rent free in a Platonic heaven of ideal mathematical models. That is, a model can be arbitrarily detailed and can contain an arbitrary amount of information without affecting the universes they describe. But we are not angels, who view the universe from the outside. Instead, we and our models are both part of the universe we are describing. Thus a physical theory is self referencing, like in Godel's theorem. One might therefore expect it to be either inconsistent or incomplete. The theories we have so far are both inconsistent and incomplete.

Quantum gravity is essential to the argument. The information in the model can be represented by an arrangement of particles. According to quantum theory, a particle in a region of a given size has a certain minimum amount of energy. Thus, as I said earlier, models don't live rent free. They cost energy. By Einstein's famous equation, E = mc squared, energy is equivalent to mass. And mass causes systems to collapse under gravity. It is like getting too many books together in a library. The floor would give way and create a black hole that would swallow the information. Remarkably enough, Jacob Bekenstein and I found that the amount of information in a black hole is proportional to the area of the boundary of the hole, rather than the volume of the hole, as one might have expected. The black hole limit on the concentration of information is fundamental, but it has not been properly incorporated into any of the formulations of M theory that we have so far. They all assume that one can define the wave function at each point of space. But that would be an infinite density of information which is not allowed. On the other hand, if one can't define the wave function point wise, one can't predict the future to arbitrary accuracy, even in the reduced determinism of quantum theory. What we need is a formulation of M theory that takes account of the black hole information limit. But then our experience with supergravity and string theory, and the analogy of Godel’s theorem, suggest that even this formulation will be incomplete.

Some people will be very disappointed if there is not an ultimate theory that can be formulated as a finite number of principles. I used to belong to that camp, but I have changed my mind. I'm now glad that our search for understanding will never come to an end, and that we will always have the challenge of new discovery. Without it, we would stagnate. Godel’s theorem ensured there would always be a job for mathematicians. I think M theory will do the same for physicists. I'm sure Dirac would have approved.

Thank you for listening.

Space and Time Warps



In science fiction, space and time warps are a commonplace. They are used for rapid journeys around the galaxy, or for travel through time. But today's science fiction, is often tomorrow's science fact. So what are the chances for space and time warps.

The idea that space and time can be curved, or warped, is fairly recent. For more than two thousand years, the axioms of Euclidean geometry, were considered to be self evident. As those of you that were forced to learn Euclidean geometry at school may remember, one of the consequences of these axioms is, that the angles of a triangle, add up to a hundred and 80 degrees.

However, in the last century, people began to realize that other forms of geometry were possible, in which the angles of a triangle, need not add up to a hundred and 80 degrees. Consider, for example, the surface of the Earth. The nearest thing to a straight line on the surface of the Earth, is what is called, a great circle. These are the shortest paths between two points, so they are the roots that air lines use. Consider now the triangle on the surface of the Earth, made up of the equator, the line of 0 degrees longitude through London, and the line of 90 degrees longtitude east, through Bangladesh. The two lines of longitude, meet the equator at a right angle, 90 degrees. The two lines of longitude also meet each other at the north pole, at a right angle, or 90 degrees. Thus one has a triangle with three right angles. The angles of this triangle add up to two hundred and seventy degrees. This is greater than the hundred and eighty degrees, for a triangle on a flat surface. If one drew a triangle on a saddle shaped surface, one would find that the angles added up to less than a hundred and eighty degrees. The surface of the Earth, is what is called a two dimensional space. That is, you can move on the surface of the Earth, in two directions at right angles to each other: you can move north south, or east west. But of course, there is a third direction at right angles to these two, and that is up or down. That is to say, the surface of the Earth exists in three-dimensional space. The three dimensional space is flat. That is to say, it obeys Euclidean geometry. The angles of a triangle, add up to a hundred and eighty degrees. However, one could imagine a race of two dimensional creatures, who could move about on the surface of the Earth, but who couldn't experience the third direction, of up or down. They wouldn't know about the flat three-dimensional space, in which the surface of the Earth lives. For them, space would be curved, and geometry would be non-Euclidean.

It would be very difficult to design a living being that could exist in only two dimensions.

Food that the creature couldn't digest would have to be spat out the same way it came in. If there were a passage right the way through, like we have, the poor animal would fall apart.

So three dimensions, seems to be the minimum for life. But just as one can think of two dimensional beings living on the surface of the Earth, so one could imagine that the three dimensional space in which we live, was the surface of a sphere, in another dimension that we don't see. If the sphere were very large, space would be nearly flat, and Euclidean geometry would be a very good approximation over small distances. But we would notice that Euclidean geometry broke down, over large distances.

As an illustration of this, imagine a team of painters, adding paint to the surface of a large ball. As the thickness of the paint layer increased, the surface area would go up. If the ball were in a flat three-dimensional space, one could go on adding paint indefinitely, and the ball would get bigger and bigger. However, if the three-dimensional space, were really the surface of a sphere in another dimension, its volume would be large but finite. As one added more layers of paint, the ball would eventually fill half the space. After that, the painters would find that they were trapped in a region of ever decreasing size, and almost the whole of space, was occupied by the ball, and its layers of paint. So they would know that they were living in a curved space, and not a flat one. This example shows that one can not deduce the geometry of the world from first principles, as the ancient Greeks thought. Instead, one has to measure the space we live in, and find out its geometry by experiment. However, although a way to describe curved spaces, was developed by the German, George Friedrich Riemann, in 1854, it remained just a piece of mathematics for sixty years. It could describe curved spaces that existed in the abstract, but there seemed no reason why the physical space we lived in, should be curved. This came only in 1915, when Einstein put forward the General Theory of Relativity.

General Relativity was a major intellectual revolution that has transformed the way we think about the universe. It is a theory not only of curved space, but of curved or warped time as well. Einstein had realized in 1905, that space and time, are intimately connected with each other. One can describe the location of an event by four numbers. Three numbers describe the position of the event. They could be miles north and east of Oxford circus, and height above sea level. On a larger scale, they could be galactic latitude and longitude, and distance from the center of the galaxy. The fourth number, is the time of the event. Thus one can think of space and time together, as a four-dimensional entity, called space-time. Each point of space-time is labeled by four numbers, that specify its position in space, and in time. Combining space and time into space-time in this way would be rather trivial, if one could disentangle them in a unique way. That is to say, if there was a unique way of defining the time and position of each event. However, in a remarkable paper written in 1905, when he was a clerk in the Swiss patent office, Einstein showed that the time and position at which one thought an event occurred, depended on how one was moving. This meant that time and space, were inextricably bound up with each other. The times that different observers would assign to events would agree if the observers were not moving relative to each other. But they would disagree more, the faster their relative speed. So one can ask, how fast does one need to go, in order that the time for one observer, should go backwards relative to the time of another observer. The answer is given in the following Limerick.

There was a young lady of Wight,

Who traveled much faster than light,

She departed one day,

In a relative way,

And arrived on the previous night.

So all we need for time travel, is a space ship that will go faster than light. Unfortunately, in the same paper, Einstein showed that the rocket power needed to accelerate a space ship, got greater and greater, the nearer it got to the speed of light. So it would take an infinite amount of power, to accelerate past the speed of light.

Einstein's paper of 1905 seemed to rule out time travel into the past. It also indicated that space travel to other stars, was going to be a very slow and tedious business. If one couldn't go faster than light, the round trip to the nearest star, would take at least eight years, and to the center of the galaxy, at least eighty thousand years. If the space ship went very near the speed of light, it might seem to the people on board, that the trip to the galactic center had taken only a few years. But that wouldn't be much consolation, if everyone you had known was dead and forgotten thousands of years ago, when you got back. That wouldn't be much good for space Westerns. So writers of science fiction, had to look for ways to get round this difficulty.

In his 1915 paper, Einstein showed that the effects of gravity could be described, by supposing that space-time was warped or distorted, by the matter and energy in it. We can actually observe this warping of space-time, produced by the mass of the Sun, in the slight bending of light or radio waves, passing close to the Sun. This causes the apparent position of the star or radio source, to shift slightly, when the Sun is between the Earth and the source. The shift is very small, about a thousandth of a degree, equivalent to a movement of an inch, at a distance of a mile. Nevertheless, it can be measured with great accuracy, and it agrees with the predictions of General Relativity. We have experimental evidence, that space and time are warped. The amount of warping in our neighbourhood, is very small, because all the gravitational fields in the solar system, are weak. However, we know that very strong fields can occur, for example in the Big Bang, or in black holes. So, can space and time be warped enough, to meet the demands from science fiction, for things like hyper space drives, wormholes, or time travel. At first sight, all these seem possible. For example, in 1948, Kurt Goedel found a solution of the field equations of General Relativity, which represents a universe in which all the matter was rotating. In this universe, it would be possible to go off in a space ship, and come back before you set out. Goedel was at the Institute of Advanced Study, in Princeton, where Einstein also spent his last years. He was more famous for proving you couldn't prove everything that is true, even in such an apparently simple subject as arithmetic. But what he proved about General Relativity allowing time travel really upset Einstein, who had thought it wouldn't be possible.

We now know that Goedel's solution couldn't represent the universe in which we live, because it was not expanding. It also had a fairly large value for a quantity called the cosmological constant, which is generally believed to be zero. However, other apparently more reasonable solutions that allow time travel, have since been found. A particularly interesting one contains two cosmic strings, moving past each other at a speed very near to, but slightly less than, the speed of light. Cosmic strings are a remarkable idea of theoretical physics, which science fiction writers don't really seem to have caught on to. As their name suggests, they are like string, in that they have length, but a tiny cross section. Actually, they are more like rubber bands, because they are under enormous tension, something like a hundred billion billion billion tons. A cosmic string attached to the Sun would accelerate it naught to sixty, in a thirtieth of a second.

Cosmic strings may sound far-fetched, and pure science fiction, but there are good scientific reasons to believed they could have formed in the very early universe, shortly after the Big Bang. Because they are under such great tension, one might have expected them to accelerate to almost the speed of light.

What both the Goedel universe, and the fast moving cosmic string space-time have in common, is that they start out so distorted and curved, that travel into the past, was always possible. God might have created such a warped universe, but we have no reason to think that He did. All the evidence is, that the universe started out in the Big Bang, without the kind of warping needed, to allow travel into the past. Since we can't change the way the universe began, the question of whether time travel is possible, is one of whether we can subsequently make space-time so warped, that one can go back to the past. I think this is an important subject for research, but one has to be careful not to be labeled a crank. If one made a research grant application to work on time travel, it would be dismissed immediately. No government agency could afford to be seen to be spending public money, on anything as way out as time travel. Instead, one has to use technical terms, like closed time like curves, which are code for time travel. Although this lecture is partly about time travel, I felt I had to give it the scientifically more respectable title, Space and Time warps. Yet, it is a very serious question. Since General Relativity can permit time travel, does it allow it in our universe? And if not, why not.

Closely related to time travel, is the ability to travel rapidly from one position in space, to another. As I said earlier, Einstein showed that it would take an infinite amount of rocket power, to accelerate a space ship to beyond the speed of light. So the only way to get from one side of the galaxy to the other, in a reasonable time, would seem to be if we could warp space-time so much, that we created a little tube or wormhole. This could connect the two sides of the galaxy, and act as a short cut, to get from one to the other and back while your friends were still alive. Such wormholes have been seriously suggested, as being within the capabilities of a future civilization. But if you can travel from one side of the galaxy, to the other, in a week or two, you could go back through another wormhole, and arrive back before you set out. You could even manage to travel back in time with a single wormhole, if its two ends were moving relative to each other.

One can show that to create a wormhole, one needs to warp space-time in the opposite way, to that in which normal matter warps it. Ordinary matter curves space-time back on itself, like the surface of the Earth.

However, to create a wormhole, one needs matter that warps space-time in the opposite way, like the surface of a saddle. The same is true of any other way of warping space-time to allow travel to the past, if the universe didn't begin so warped, that it allowed time travel. What one would need, would be matter with negative mass, and negative energy density, to make space-time warp in the way required.

Energy is rather like money. If you have a positive bank balance, you can distribute it in various ways. But according to the classical laws that were believed until quite recently, you weren't allowed to have an energy overdraft. So these classical laws would have ruled out us being able to warp the universe, in the way required to allow time travel. However, the classical laws were overthrown by Quantum Theory, which is the other great revolution in our picture of the universe, apart from General Relativity. Quantum Theory is more relaxed, and allows you to have an overdraft on one or two accounts. If only the banks were as accommodating. In other words, Quantum Theory allows the energy density to be negative in some places, provided it is positive in others.

The reason Quantum Theory can allow the energy density to be negative, is that it is based on the Uncertainty Principle.

This says that certain quantities, like the position and speed of a particle, can't both have well defined values. The more accurately the position of a particle is defined, the greater is the uncertainty in its speed, and vice versa. The uncertainty principle also applies to fields, like the electro-magnetic field, or the gravitational field. It implies that these fields can't be exactly zeroed, even in what we think of as empty space. For if they were exactly zero, their values would have both a well-defined position at zero, and a well-defined speed, which was also zero. This would be a violation of the uncertainty principle. Instead, the fields would have to have a certain minimum amount of fluctuations. One can interpret these so called vacuum fluctuations, as pairs of particles and anti particles, that suddenly appear together, move apart, and then come back together again, and annihilate each other. These particle anti particle pairs, are said to be virtual, because one cannot measure them directly with a particle detector. However, one can observe their effects indirectly. One way of doing this, is by what is called the Casimir effect. One has two parallel metal plates, a short distance apart. The plates act like mirrors for the virtual particles and anti particles. This means that the region between the plates, is a bit like an organ pipe, and will only admit light waves of certain resonant frequencies. The result is that there are slightly fewer vacuum fluctuations, or virtual particles, between the plates, than outside them, where vacuum fluctuations can have any wavelength. The reduction in the number of virtual particles between the plates means that they don't hit the plates so often, and thus don't exert as much pressure on the plates, as the virtual particles outside. There is thus a slight force pushing the plates together. This force has been measured experimentally. So virtual particles actually exist, and produce real effects.

Because there are fewer virtual particles, or vacuum fluctuations, between the plates, they have a lower energy density, than in the region outside. But the energy density of empty space far away from the plates, must be zero. Otherwise it would warp space-time, and the universe wouldn't be nearly flat. So the energy density in the region between the plates, must be negative.

We thus have experimental evidence from the bending of light, that space-time is curved, and confirmation from the Casimir effect, that we can warp it in the negative direction. So it might seem possible, that as we advance in science and technology, we might be able to construct a wormhole, or warp space and time in some other way, so as to be able to travel into our past. If this were the case, it would raise a whole host of questions and problems. One of these is, if sometime in the future, we learn to travel in time, why hasn't someone come back from the future, to tell us how to do it.

Even if there were sound reasons for keeping us in ignorance, human nature being what it is, it is difficult to believe that someone wouldn't show off, and tell us poor benighted peasants, the secret of time travel. Of course, some people would claim that we have been visited from the future. They would say that UFO's come from the future, and that governments are engaged in a gigantic conspiracy to cover them up, and keep for themselves, the scientific knowledge that these visitors bring. All I can say is, that if governments were hiding something, they are doing a pretty poor job, of extracting useful information from the aliens. I'm pretty skeptical of conspiracy theories, believing the cock up theory is more likely. The reports of sightings of UFO's can't all be caused by extra terrestrials, because they are mutually contradictory. But once you admit that some are mistakes, or hallucinations, isn't it more probable that they all are, than that we are being visited by people from the future, or the other side of the galaxy? If they really want to colonize the Earth, or warn us of some danger, they are being pretty ineffective. A possible way to reconcile time travel, with the fact that we don't seem to have had any visitors from the future, would be to say that it can occur only in the future. In this view, one would say space-time in our past was fixed, because we have observed it, and seen that it is not warped enough, to allow travel into the past. On the other hand, the future is open. So we might be able to warp it enough, to allow time travel. But because we can warp space-time only in the future, we wouldn't be able to travel back to the present time, or earlier.

This picture would explain why we haven't been overrun by tourists from the future. But it would still leave plenty of paradoxes. Suppose it were possible to go off in a rocket ship, and come back before you set off. What would stop you blowing up the rocket on its launch pad, or otherwise preventing you from setting out in the first place. There are other versions of this paradox, like going back, and killing your parents before you were born, but they are essentially equivalent. There seem to be two possible resolutions.

One is what I shall call, the consistent histories approach. It says that one has to find a consistent solution of the equations of physics, even if space-time is so warped, that it is possible to travel into the past. On this view, you couldn't set out on the rocket ship to travel into the past, unless you had already come back, and failed to blow up the launch pad. It is a consistent picture, but it would imply that we were completely determined: we couldn't change our minds. So much for free will. The other possibility is what I call, the alternative histories approach. It has been championed by the physicist David Deutsch, and it seems to have been what Stephen Spielberg had in mind when he filmed, Back to the Future.

In this view, in one alternative history, there would not have been any return from the future, before the rocket set off, and so no possibility of it being blown up. But when the traveler returns from the future, he enters another alternative history. In this, the human race makes a tremendous effort to build a space ship, but just before it is due to be launched, a similar space ship appears from the other side of the galaxy, and destroys it. David Deutsch claims support for the alternative histories approach, from the sum over histories concept, introduced by the physicist, Richard Feinman, who died a few years ago. The idea is that according to Quantum Theory, the universe doesn't have just a unique single history.

Instead, the universe has every single possible history, each with its own probability. There must be a possible history in which there is a lasting peace in the Middle East, though maybe the probability is low. In some histories space-time will be so warped, that objects like rockets will be able to travel into their pasts. But each history is complete and self contained, describing not only the curved space-time, but also the objects in it. So a rocket can not transfer to another alternative history, when it comes round again. It is still in the same history, which has to be self consistent. Thus, despite what

Deutsch claims, I think the sum over histories idea, supports the consistent histories hypothesis, rather than the alternative histories idea.

It thus seems that we are stuck with the consistent histories picture. However, this need not involve problems with determinism or free will, if the probabilities are very small, for histories in which space-time is so warped, that time travel is possible over a macroscopic region. This is what I call, the Chronology Protection Conjecture: the laws of physics conspire to prevent time travel, on a macroscopic scale.

It seems that what happens, is that when space-time gets warped almost enough to allow travel into the past, virtual particles can almost become real particles, following closed trajectories. The density of the virtual particles, and their energy, become very large. This means that the probability of these histories is very low. Thus it seems there may be a Chronology Protection Agency at work, making the world safe for historians. But this subject of space and time warps is still in its infancy. According to string theory, which is our best hope of uniting General Relativity and Quantum Theory, into a Theory of Everything, space-time ought to have ten dimensions, not just the four that we experience. The idea is that six of these ten dimensions are curled up into a space so small, that we don't notice them. On the other hand, the remaining four directions are fairly flat, and are what we call space-time. If this picture is correct, it might be possible to arrange that the four flat directions got mixed up with the six highly curved or warped directions. What this would give rise to, we don't yet know. But it opens exciting possibilities.

The conclusion of this lecture is that rapid space-travel, or travel back in time, can't be ruled out, according to our present understanding. They would cause great logical problems, so let's hope there's a Chronology Protection Law, to prevent people going back, and killing our parents. But science fiction fans need not lose heart. There's hope in string theory.

Since we haven't cracked time travel yet, I have run out of time. Thank you for listening.

Does God play Dice?

This lecture is about whether we can predict the future, or whether it is arbitrary and random. In ancient times, the world must have seemed pretty arbitrary. Disasters such as floods or diseases must have seemed to happen without warning, or apparent reason. Primitive people attributed such natural phenomena, to a pantheon of gods and goddesses, who behaved in a capricious and whimsical way. There was no way to predict what they would do, and the only hope was to win favour by gifts or actions. Many people still partially subscribe to this belief, and try to make a pact with fortune. They offer to do certain things, if only they can get an A-grade for a course, or pass their driving test.

Gradually however, people must have noticed certain regularities in the behaviour of nature. These regularities were most obvious, in the motion of the heavenly bodies across the sky. So astronomy was the first science to be developed. It was put on a firm mathematical basis by Newton, more than 300 years ago, and we still use his theory of gravity to predict the motion of almost all celestial bodies. Following the example of astronomy, it was found that other natural phenomena also obeyed definite scientific laws. This led to the idea of scientific determinism, which seems first to have been publicly expressed by the French scientist, Laplace. I thought I would like to quote you Laplace's actual words, so I asked a friend to track them down. They are in French of course, not that I expect that would be any problem with this audience. But the trouble is, Laplace was rather like Prewst, in that he wrote sentences of inordinate length and complexity. So I have decided to para-phrase the quotation. In effect what he said was, that if at one time, we knew the positions and speeds of all the particles in the universe, then we could calculate their behaviour at any other time, in the past or future. There is a probably apocryphal story, that when Laplace was asked by Napoleon, how God fitted into this system, he replied, 'Sire, I have not needed that hypothesis.' I don't think that Laplace was claiming that God didn't exist. It is just that He doesn't intervene, to break the laws of Science. That must be the position of every scientist. A scientific law, is not a scientific law, if it only holds when some supernatural being, decides to let things run, and not intervene.

The idea that the state of the universe at one time determines the state at all other times, has been a central tenet of science, ever since Laplace's time. It implies that we can predict the future, in principle at least. In practice, however, our ability to predict the future is severely limited by the complexity of the equations, and the fact that they often have a property called chaos. As those who have seen Jurassic Park will know, this means a tiny disturbance in one place, can cause a major change in another. A butterfly flapping its wings can cause rain in Central Park, New York. The trouble is, it is not repeatable. The next time the butterfly flaps its wings, a host of other things will be different, which will also influence the weather. That is why weather forecasts are so unreliable.

Despite these practical difficulties, scientific determinism, remained the official dogma throughout the 19th century. However, in the 20th century, there have been two developments that show that Laplace's vision, of a complete prediction of the future, can not be realised. The first of these developments was what is called, quantum mechanics. This was first put forward in 1900, by the German physicist, Max Planck, as an ad hoc hypothesis, to solve an outstanding paradox. According to the classical 19th century ideas, dating back to Laplace, a hot body, like a piece of red hot metal, should give off radiation. It would lose energy in radio waves, infra red, visible light, ultra violet, x-rays, and gamma rays, all at the same rate. Not only would this mean that we would all die of skin cancer, but also everything in the universe would be at the same temperature, which clearly it isn't. However, Planck showed one could avoid this disaster, if one gave up the idea that the amount of radiation could have just any value, and said instead that radiation came only in packets or quanta of a certain size. It is a bit like saying that you can't buy sugar loose in the supermarket, but only in kilogram bags. The energy in the packets or quanta, is higher for ultra violet and x-rays, than for infra red or visible light. This means that unless a body is very hot, like the Sun, it will not have enough energy, to give off even a single quantum of ultra violet or x-rays. That is why we don't get sunburn from a cup of coffee.

Planck regarded the idea of quanta, as just a mathematical trick, and not as having any physical reality, whatever that might mean. However, physicists began to find other behaviour, that could be explained only in terms of quantities having discrete, or quantised values, rather than continuously variable ones. For example, it was found that elementary particles behaved rather like little tops, spinning about an axis. But the amount of spin couldn't have just any value. It had to be some multiple of a basic unit. Because this unit is very small, one does not notice that a normal top really slows down in a rapid sequence of discrete steps, rather than as a continuous process. But for tops as small as atoms, the discrete nature of spin is very important.

It was some time before people realised the implications of this quantum behaviour for determinism. It was not until 1926, that Werner Heisenberg, another German physicist, pointed out that you couldn't measure both the position, and the speed, of a particle exactly. To see where a particle is, one has to shine light on it. But by Planck's work, one can't use an arbitrarily small amount of light. One has to use at least one quantum. This will disturb the particle, and change its speed in a way that can't be predicted. To measure the position of the particle accurately, you will have to use light of short wave length, like ultra violet, x-rays, or gamma rays. But again, by Planck's work, quanta of these forms of light have higher energies than those of visible light. So they will disturb the speed of the particle more. It is a no win situation: the more accurately you try to measure the position of the particle, the less accurately you can know the speed, and vice versa. This is summed up in the Uncertainty Principle that Heisenberg formulated; the uncertainty in the position of a particle, times the uncertainty in its speed, is always greater than a quantity called Planck's constant, divided by the mass of the particle.

Laplace's vision, of scientific determinism, involved knowing the positions and speeds of the particles in the universe, at one instant of time. So it was seriously undermined by Heisenberg's Uncertainty principle. How could one predict the future, when one could not measure accurately both the positions, and the speeds, of particles at the present time? No matter how powerful a computer you have, if you put lousy data in, you will get lousy predictions out.

Einstein was very unhappy about this apparent randomness in nature. His views were summed up in his famous phrase, 'God does not play dice'. He seemed to have felt that the uncertainty was only provisional: but that there was an underlying reality, in which particles would have well defined positions and speeds, and would evolve according to deterministic laws, in the spirit of Laplace. This reality might be known to God, but the quantum nature of light would prevent us seeing it, except through a glass darkly.

Einstein's view was what would now be called, a hidden variable theory. Hidden variable theories might seem to be the most obvious way to incorporate the Uncertainty Principle into physics. They form the basis of the mental picture of the universe, held by many scientists, and almost all philosophers of science. But these hidden variable theories are wrong. The British physicist, John Bell, who died recently, devised an experimental test that would distinguish hidden variable theories. When the experiment was carried out carefully, the results were inconsistent with hidden variables. Thus it seems that even God is bound by the Uncertainty Principle, and cannot know both the position, and the speed, of a particle. So God does play dice with the universe. All the evidence points to him being an inveterate gambler, who throws the dice on every possible occasion.

Other scientists were much more ready than Einstein to modify the classical 19th century view of determinism. A new theory, called quantum mechanics, was put forward by Heisenberg, the Austrian, Erwin Schroedinger, and the British physicist, Paul Dirac. Dirac was my predecessor but one, as the Lucasian Professor in Cambridge. Although quantum mechanics has been around for nearly 70 years, it is still not generally understood or appreciated, even by those that use it to do calculations. Yet it should concern us all, because it is a completely different picture of the physical universe, and of reality itself. In quantum mechanics, particles don't have well defined positions and speeds. Instead, they are represented by what is called a wave function. This is a number at each point of space. The size of the wave function gives the probability that the particle will be found in that position. The rate, at which the wave function varies from point to point, gives the speed of the particle. One can have a wave function that is very strongly peaked in a small region. This will mean that the uncertainty in the position is small. But the wave function will vary very rapidly near the peak, up on one side, and down on the other. Thus the uncertainty in the speed will be large. Similarly, one can have wave functions where the uncertainty in the speed is small, but the uncertainty in the position is large.

The wave function contains all that one can know of the particle, both its position, and its speed. If you know the wave function at one time, then its values at other times are determined by what is called the Schroedinger equation. Thus one still has a kind of determinism, but it is not the sort that Laplace envisaged. Instead of being able to predict the positions and speeds of particles, all we can predict is the wave function. This means that we can predict just half what we could, according to the classical 19th century view.

Although quantum mechanics leads to uncertainty, when we try to predict both the position and the speed, it still allows us to predict, with certainty, one combination of position and speed. However, even this degree of certainty, seems to be threatened by more recent developments. The problem arises because gravity can warp space-time so much, that there can be regions that we don't observe.

Interestingly enough, Laplace himself wrote a paper in 1799 on how some stars could have a gravitational field so strong that light could not escape, but would be dragged back onto the star. He even calculated that a star of the same density as the Sun, but two hundred and fifty times the size, would have this property. But although Laplace may not have realised it, the same idea had been put forward 16 years earlier by a Cambridge man, John Mitchell, in a paper in the Philosophical Transactions of the Royal Society. Both Mitchell and Laplace thought of light as consisting of particles, rather like cannon balls, that could be slowed down by gravity, and made to fall back on the star. But a famous experiment, carried out by two Americans, Michelson and Morley in 1887, showed that light always travelled at a speed of one hundred and eighty six thousand miles a second, no matter where it came from. How then could gravity slow down light, and make it fall back.

This was impossible, according to the then accepted ideas of space and time. But in 1915, Einstein put forward his revolutionary General Theory of Relativity. In this, space and time were no longer separate and independent entities. Instead, they were just different directions in a single object called space-time. This space-time was not flat, but was warped and curved by the matter and energy in it. In order to understand this, considered a sheet of rubber, with a weight placed on it, to represent a star. The weight will form a depression in the rubber, and will cause the sheet near the star to be curved, rather than flat. If one now rolls marbles on the rubber sheet, their paths will be curved, rather than being straight lines. In 1919, a British expedition to West Africa, looked at light from distant stars, that passed near the Sun during an eclipse. They found that the images of the stars were shifted slightly from their normal positions. This indicated that the paths of the light from the stars had been bent by the curved space-time near the Sun. General Relativity was confirmed.

Consider now placing heavier and heavier, and more and more concentrated weights on the rubber sheet. They will depress the sheet more and more. Eventually, at a critical weight and size, they will make a bottomless hole in the sheet, which particles can fall into, but nothing can get out of.

What happens in space-time according to General Relativity is rather similar. A star will curve and distort the space-time near it, more and more, the more massive and more compact the star is. If a massive star, which has burnt up its nuclear fuel, cools and shrinks below a critical size, it will quite literally make a bottomless hole in space-time, that light can't get out of. Such objects were given the name Black Holes, by the American physicist John Wheeler, who was one of the first to recognise their importance, and the problems they pose. The name caught on quickly. To Americans, it suggested something dark and mysterious, while to the British, there was the added resonance of the Black Hole of Calcutta. But the French, being French, saw a more risqué meaning. For years, they resisted the name, trou noir, claiming it was obscene. But that was a bit like trying to stand against le weekend, and other franglais. In the end, they had to give in. Who can resist a name that is such a winner?

We now have observations that point to black holes in a number of objects, from binary star systems, to the centre of galaxies. So it is now generally accepted that black holes exist. But, apart from their potential for science fiction, what is their significance for determinism. The answer lies in a bumper sticker that I used to have on the door of my office: Black Holes are Out of Sight. Not only do the particles and unlucky astronauts that fall into a black hole, never come out again, but also the information that they carry, is lost forever, at least from our region of the universe. You can throw television sets, diamond rings, or even your worst enemies into a black hole, and all the black hole will remember, is the total mass, and the state of rotation. John Wheeler called this, 'A Black Hole Has No Hair.' To the French, this just confirmed their suspicions.

As long as it was thought that black holes would continue to exist forever, this loss of information didn't seem to matter too much. One could say that the information still existed inside the black hole. It is just that one can't tell what it is, from the outside. However, the situation changed, when I discovered that black holes aren't completely black. Quantum mechanics causes them to send out particles and radiation at a steady rate. This result came as a total surprise to me, and everyone else. But with hindsight, it should have been obvious. What we think of as empty space is not really empty, but it is filled with pairs of particles and anti particles. These appear together at some point of space and time, move apart, and then come together and annihilate each other. These particles and anti particles occur because a field, such as the fields that carry light and gravity, can't be exactly zero. That would mean that the value of the field, would have both an exact position (at zero), and an exact speed or rate of change (also zero). This would be against the Uncertainty Principle, just as a particle can't have both an exact position, and an exact speed. So all fields must have what are called, vacuum fluctuations. Because of the quantum behaviour of nature, one can interpret these vacuum fluctuations, in terms of particles and anti particles, as I have described.

These pairs of particles occur for all varieties of elementary particles. They are called virtual particles, because they occur even in the vacuum, and they can't be directly measured by particle detectors. However, the indirect effects of virtual particles, or vacuum fluctuations, have been observed in a number of experiments, and their existence confirmed.

If there is a black hole around, one member of a particle anti particle pair may fall into the hole, leaving the other member without a partner, with which to annihilate. The forsaken particle may fall into the hole as well, but it may also escape to a large distance from the hole, where it will become a real particle, that can be measured by a particle detector. To someone a long way from the black hole, it will appear to have been emitted by the hole. This explanation of how black holes ain't so black, makes it clear that the emission will depend on the size of the black hole, and the rate at which it is rotating. But because black holes have no hair, in Wheeler's phrase, the radiation will be otherwise independent of what went into the hole. It doesn't matter whether you throw television sets, diamond rings, or your worst enemies, into a black hole. What comes back out will be the same.

So what has all this to do with determinism, which is what this lecture is supposed to be about. What it shows is that there are many initial states, containing television sets, diamond rings, and even people, that evolve to the same final state, at least outside the black hole. But in Laplace's picture of determinism, there was a one to one correspondence between initial states, and final states. If you knew the state of the universe at some time in the past, you could predict it in the future. Similarly, if you knew it in the future, you could calculate what it must have been in the past. The advent of quantum theory in the 1920s reduced the amount one could predict by half, but it still left a one to one correspondence between the states of the universe at different times. If one knew the wave function at one time, one could calculate it at any other time.

With black holes, however, the situation is rather different. One will end up with the same state outside the hole, whatever one threw in, provided it has the same mass. Thus there is not a one to one correspondence between the initial state, and the final state outside the black hole. There will be a one to one correspondence between the initial state, and the final state both outside, and inside, the black hole. But the important point is that the emission of particles, and radiation by the black hole, will cause the hole to lose mass, and get smaller. Eventually, it seems the black hole will get down to zero mass, and will disappear altogether. What then will happen to all the objects that fell into the hole, and all the people that either jumped in, or were pushed? They can't come out again, because there isn't enough mass or energy left in the black hole, to send them out again. They may pass into another universe, but that is not something that will make any difference, to those of us prudent enough not to jump into a black hole. Even the information, about what fell into the hole, could not come out again when the hole finally disappears. Information can not be carried free, as those of you with phone bills will know. Information requires energy to carry it, and there won't be enough energy left when the black hole disappears.

What all this means is, that information will be lost from our region of the universe, when black holes are formed, and then evaporate. This loss of information will mean that we can predict even less than we thought, on the basis of quantum theory. In quantum theory, one may not be able to predict with certainty, both the position, and the speed of a particle. But there is still one combination of position and speed that can be predicted. In the case of a black hole, this definite prediction involves both members of a particle pair. But we can measure only the particle that comes out. There's no way even in principle that we can measure the particle that falls into the hole. So, for all we can tell, it could be in any state. This means we can not make any definite prediction, about the particle that escapes from the hole. We can calculate the probability that the particle has this or that position, or speed. But there's no combination of the position and speed of just one particle that we can definitely predict, because the speed and position will depend on the other particle, which we don't observe. Thus it seems Einstein was doubly wrong when he said, God does not play dice. Not only does God definitely play dice, but He sometimes confuses us by throwing them where they can't be seen.

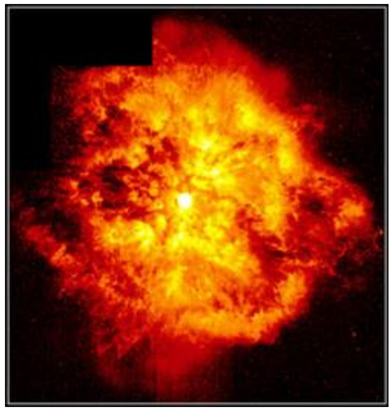
Many scientists are like Einstein, in that they have a deep emotional attachment to determinism. Unlike Einstein, they have accepted the reduction in our ability to predict, that quantum theory brought about. But that was far enough. They didn't like the further reduction, which black holes seemed to imply. They have therefore claimed that information is not really lost down black holes. But they have not managed to find any mechanism that would return the information. It is just a pious hope that the universe is deterministic, in the way that Laplace thought. I feel these scientists have not learnt the lesson of history. The universe does not behave according to our pre-conceived ideas. It continues to surprise us.

One might not think it mattered very much, if determinism broke down near black holes. We are almost certainly at least a few light years, from a black hole of any size. But, the Uncertainty Principle implies that every region of space should be full of tiny virtual black holes, which appear and disappear again. One would think that particles and information could fall into these black holes, and be lost. Because these virtual black holes are so small, a hundred billion billion times smaller than the nucleus of an atom, the rate at which information would be lost would be very low. That is why the laws of science appear deterministic, to a very good approximation. But in extreme conditions, like in the early universe, or in high energy particle collisions, there could be significant loss of information. This would lead to unpredictability, in the evolution of the universe.

To sum up, what I have been talking about, is whether the universe evolves in an arbitrary way, or whether it is deterministic. The classical view, put forward by Laplace, was that the future motion of particles was completely determined, if one knew their positions and speeds at one time. This view had to be modified, when Heisenberg put forward his Uncertainty Principle, which said that one could not know both the position, and the speed, accurately. However, it was still possible to predict one combination of position and speed. But even this limited predictability disappeared, when the effects of black holes were taken into account. The loss of particles and information down black holes meant that the particles that came out were random. One could calculate probabilities, but one could not make any definite predictions. Thus, the future of the universe is not completely determined by the laws of science, and its present state, as Laplace thought. God still has a few tricks up his sleeve.

That is all I have to say for the moment. Thank you for listening.

The Beginning of Time



In this lecture, I would like to discuss whether time itself has a beginning, and whether it will have an end. All the evidence seems to indicate, that the universe has not existed forever, but that it had a beginning, about 15 billion years ago. This is probably the most remarkable discovery of modern cosmology. Yet it is now taken for granted. We are not yet certain whether the universe will have an end. When I gave a lecture in Japan, I was asked not to mention the possible re-collapse of the universe, because it might affect the stock market. However, I can re-assure anyone who is nervous about their investments that it is a bit early to sell: even if the universe does come to an end, it won't be for at least twenty billion years. By that time, maybe the GATT trade agreement will have come into effect.

The time scale of the universe is very long compared to that for human life. It was therefore not surprising that until recently, the universe was thought to be essentially static, and unchanging in time. On the other hand, it must have been obvious, that society is evolving in culture and technology. This indicates that the present phase of human history can not have been going for more than a few thousand years. Otherwise, we would be more advanced than we are. It was therefore natural to believe that the human race, and maybe the whole universe, had a beginning in the fairly recent past. However, many people were unhappy with the idea that the universe had a beginning, because it seemed to imply the existence of a supernatural being who created the universe. They preferred to believe that the universe, and the human race, had existed forever. Their explanation for human progress was that there had been periodic floods, or other natural disasters, which repeatedly set back the human race to a primitive state.

This argument about whether or not the universe had a beginning, persisted into the 19th and 20th centuries. It was conducted mainly on the basis of theology and philosophy, with little consideration of observational evidence. This may have been reasonable, given the notoriously unreliable character of cosmological observations, until fairly recently. The cosmologist, Sir Arthur Eddington, once said, 'Don't worry if your theory doesn't agree with the observations, because they are probably wrong.' But if your theory disagrees with the Second Law of Thermodynamics, it is in bad trouble. In fact, the theory that the universe has existed forever is in serious difficulty with the Second Law of Thermodynamics. The Second Law, states that disorder always increases with time. Like the argument about human progress, it indicates that there must have been a beginning. Otherwise, the universe would be in a state of complete disorder by now, and everything would be at the same temperature. In an infinite and everlasting universe, every line of sight would end on the surface of a star. This would mean that the night sky would have been as bright as the surface of the Sun. The only way of avoiding this problem would be if, for some reason, the stars did not shine before a certain time.

In a universe that was essentially static, there would not have been any dynamical reason, why the stars should have suddenly turned on, at some time. Any such "lighting up time" would have to be imposed by an intervention from outside the universe. The situation was different, however, when it was realised that the universe is not static, but expanding. Galaxies are moving steadily apart from each other. This means that they were closer together in the past. One can plot the separation of two galaxies, as a function of time. If there were no acceleration due to gravity, the graph would be a straight line. It would go down to zero separation, about twenty billion years ago. One would expect gravity, to cause the galaxies to accelerate towards each other. This will mean that the graph of the separation of two galaxies will bend downwards, below the straight line. So the time of zero separation, would have been less than twenty billion years ago.

At this time, the Big Bang, all the matter in the universe, would have been on top of itself. The density would have been infinite. It would have been what is called, a singularity. At a singularity, all the laws of physics would have broken down. This means that the state of the universe, after the Big Bang, will not depend on anything that may have happened before, because the deterministic laws that govern the universe will break down in the Big Bang. The universe will evolve from the Big Bang, completely independently of what it was like before. Even the amount of matter in the universe, can be different to what it was before the Big Bang, as the Law of Conservation of Matter, will break down at the Big Bang.

Since events before the Big Bang have no observational consequences, one may as well cut them out of the theory, and say that time began at the Big Bang. Events before the Big Bang, are simply not defined, because there's no way one could measure what happened at them. This kind of beginning to the universe, and of time itself, is very different to the beginnings that had been considered earlier. These had to be imposed on the universe by some external agency. There is no dynamical reason why the motion of bodies in the solar system can not be extrapolated back in time, far beyond four thousand and four BC, the date for the creation of the universe, according to the book of Genesis. Thus it would require the direct intervention of God, if the universe began at that date. By contrast, the Big Bang is a beginning that is required by the dynamical laws that govern the universe. It is therefore intrinsic to the universe, and is not imposed on it from outside.

Although the laws of science seemed to predict the universe had a beginning, they also seemed to predict that they could not determine how the universe would have begun. This was obviously very unsatisfactory. So there were a number of attempts to get round the conclusion, that there was a singularity of infinite density in the past. One suggestion was to modify the law of gravity, so that it became repulsive. This could lead to the graph of the separation between two galaxies, being a curve that approached zero, but didn't actually pass through it, at any finite time in the past. Instead, the idea was that, as the galaxies moved apart, new galaxies were formed in between, from matter that was supposed to be continually created. This was the Steady State theory, proposed by Bondi, Gold, and Hoyle.

The Steady State theory, was what Karl Popper would call, a good scientific theory: it made definite predictions, which could be tested by observation, and possibly falsified. Unfortunately for the theory, they were falsified. The first trouble came with the Cambridge observations, of the number of radio sources of different strengths. On average, one would expect that the fainter sources would also be the more distant. One would therefore expect them to be more numerous than bright sources, which would tend to be near to us. However, the graph of the number of radio sources, against there strength, went up much more sharply at low source strengths, than the Steady State theory predicted.

There were attempts to explain away this number count graph, by claiming that some of the faint radio sources, were within our own galaxy, and so did not tell us anything about cosmology. This argument didn't really stand up to further observations. But the final nail in the coffin of the Steady State theory came with the discovery of the microwave background radiation, in 1965. This radiation is the same in all directions. It has the spectrum of radiation in thermal equilibrium at a temperature of 2 point 7 degrees above the Absolute Zero of temperature. There doesn't seem any way to explain this radiation in the Steady State theory.

Another attempt to avoid a beginning to time, was the suggestion, that maybe all the galaxies didn't meet up at a single point in the past. Although on average, the galaxies are moving apart from each other at a steady rate, they also have small additional velocities, relative to the uniform expansion. These so-called "peculiar velocities" of the galaxies, may be directed sideways to the main expansion. It was argued, that as you plotted the position of the galaxies back in time, the sideways peculiar velocities, would have meant that the galaxies wouldn't have all met up. Instead, there could have been a previous contracting phase of the universe, in which galaxies were moving towards each other. The sideways velocities could have meant that the galaxies didn't collide, but rushed past each other, and then started to move apart. There wouldn't have been any singularity of infinite density, or any breakdown of the laws of physics. Thus there would be no necessity for the universe, and time itself, to have a beginning. Indeed, one might suppose that the universe had oscillated, though that still wouldn't solve the problem with the Second Law of Thermodynamics: one would expect that the universe would become more disordered each oscillation. It is therefore difficult to see how the universe could have been oscillating for an infinite time.

This possibility, that the galaxies would have missed each other, was supported by a paper by two Russians. They claimed that there would be no singularities in a solution of the field equations of general relativity, which was fully general, in the sense that it didn't have any exact symmetry. However, their claim was proved wrong, by a number of theorems by Roger Penrose and myself. These showed that general relativity predicted singularities, whenever more than a certain amount of mass was present in a region. The first theorems were designed to show that time came to an end, inside a black hole, formed by the collapse of a star. However, the expansion of the universe, is like the time reverse of the collapse of a star. I therefore want to show you, that observational evidence indicates the universe contains sufficient matter, that it is like the time reverse of a black hole, and so contains a singularity.

In order to discuss observations in cosmology, it is helpful to draw a diagram of events in space and time, with time going upward, and the space directions horizontal. To show this diagram properly, I would really need a four dimensional screen. However, because of government cuts, we could manage to provide only a two dimensional screen. I shall therefore be able to show only one of the space directions.

As we look out at the universe, we are looking back in time, because light had to leave distant objects a long time ago, to reach us at the present time. This means that the events we observe lie on what is called our past light cone. The point of the cone is at our position, at the present time. As one goes back in time on the diagram, the light cone spreads out to greater distances, and its area increases. However, if there is sufficient matter on our past light cone, it will bend the rays of light towards each other. This will mean that, as one goes back into the past, the area of our past light cone will reach a maximum, and then start to decrease. It is this focussing of our past light cone, by the gravitational effect of the matter in the universe, that is the signal that the universe is within its horizon, like the time reverse of a black hole. If one can determine that there is enough matter in the universe, to focus our past light cone, one can then apply the singularity theorems, to show that time must have a beginning.

How can we tell from the observations, whether there is enough matter on our past light cone, to focus it? We observe a number of galaxies, but we cannot measure directly how much matter they contain. Nor can we be sure that every line of sight from us will pass through a galaxy. So I will give a different argument, to show that the universe contains enough matter, to focus our past light cone. The argument is based on the spectrum of the microwave background radiation. This is characteristic of radiation that has been in thermal equilibrium, with matter at the same temperature. To achieve such an equilibrium, it is necessary for the radiation to be scattered by matter, many times. For example, the light that we receive from the Sun has a characteristically thermal spectrum. This is not because the nuclear reactions, which go on in the centre of the Sun, produce radiation with a thermal spectrum. Rather, it is because the radiation has been scattered, by the matter in the Sun, many times on its way from the centre.

In the case of the universe, the fact that the microwave background has such an exactly thermal spectrum indicates that it must have been scattered many times. The universe must therefore contain enough matter, to make it opaque in every direction we look, because the microwave background is the same, in every direction we look. Moreover, this opacity must occur a long way away from us, because we can see galaxies and quasars, at great distances. Thus there must be a lot of matter at a great distance from us. The greatest opacity over a broad wave band, for a given density, comes from ionised hydrogen. It then follows that if there is enough matter to make the universe opaque, there is also enough matter to focus our past light cone. One can then apply the theorem of Penrose and myself, to show that time must have a beginning.

The focussing of our past light cone implied that time must have a beginning, if the General Theory of relativity is correct. But one might raise the question, of whether General Relativity really is correct. It certainly agrees with all the observational tests that have been carried out. However these test General Relativity, only over fairly large distances. We know that General Relativity cannot be quite correct on very small distances, because it is a classical theory. This means, it doesn't take into account, the Uncertainty Principle of Quantum Mechanics, which says that an object cannot have both a well defined position, and a well defined speed: the more accurately one measures the position, the less accurately one can measure the speed, and vice versa. Therefore, to understand the very high-density stage, when the universe was very small, one needs a quantum theory of gravity, which will combine General Relativity with the Uncertainty Principle.

Many people hoped that quantum effects, would somehow smooth out the singularity of infinite density, and allow the universe to bounce, and continue back to a previous contracting phase. This would be rather like the earlier idea of galaxies missing each other, but the bounce would occur at a much higher density. However, I think that this is not what happens: quantum effects do not remove the singularity, and allow time to be continued back indefinitely. But it seems that quantum effects can remove the most objectionable feature, of singularities in classical General Relativity. This is that the classical theory, does not enable one to calculate what would come out of a singularity, because all the Laws of Physics would break down there. This would mean that science could not predict how the universe would have begun. Instead, one would have to appeal to an agency outside the universe. This may be why many religious leaders, were ready to accept the Big Bang, and the singularity theorems.

It seems that Quantum theory, on the other hand, can predict how the universe will begin. Quantum theory introduces a new idea, that of imaginary time. Imaginary time may sound like science fiction, and it has been brought into Doctor Who. But nevertheless, it is a genuine scientific concept. One can picture it in the following way. One can think of ordinary, real, time as a horizontal line. On the left, one has the past, and on the right, the future. But there's another kind of time in the vertical direction. This is called imaginary time, because it is not the kind of time we normally experience. But in a sense, it is just as real, as what we call real time.

The three directions in space, and the one direction of imaginary time, make up what is called a Euclidean space-time. I don't think anyone can picture a four dimensional curve space. But it is not too difficult to visualise a two dimensional surface, like a saddle, or the surface of a football.

In fact, James Hartle of the University of California Santa Barbara, and I have proposed that space and imaginary time together, are indeed finite in extent, but without boundary. They would be like the surface of the Earth, but with two more dimensions. The surface of the Earth is finite in extent, but it doesn't have any boundaries or edges. I have been round the world, and I didn't fall off.

If space and imaginary time are indeed like the surface of the Earth, there wouldn't be any singularities in the imaginary time direction, at which the laws of physics would break down. And there wouldn't be any boundaries, to the imaginary time space-time, just as there aren't any boundaries to the surface of the Earth. This absence of boundaries means that the laws of physics would determine the state of the universe uniquely, in imaginary time. But if one knows the state of the universe in imaginary time, one can calculate the state of the universe in real time. One would still expect some sort of Big Bang singularity in real time. So real time would still have a beginning. But one wouldn't have to appeal to something outside the universe, to determine how the universe began. Instead, the way the universe started out at the Big Bang would be determined by the state of the universe in imaginary time. Thus, the universe would be a completely self-contained system. It would not be determined by anything outside the physical universe, that we observe.

The no boundary condition, is the statement that the laws of physics hold everywhere. Clearly, this is something that one would like to believe, but it is a hypothesis. One has to test it, by comparing the state of the universe that it would predict, with observations of what the universe is actually like. If the observations disagreed with the predictions of the no boundary hypothesis, we would have to conclude the hypothesis was false. There would have to be something outside the universe, to wind up the clockwork, and set the universe going. Of course, even if the observations do agree with the predictions, that does not prove that the no boundary proposal is correct. But one's confidence in it would be increased, particularly because there doesn't seem to be any other natural proposal, for the quantum state of the universe.

The no boundary proposal, predicts that the universe would start at a single point, like the North Pole of the Earth. But this point wouldn't be a singularity, like the Big Bang. Instead, it would be an ordinary point of space and time, like the North Pole is an ordinary point on the Earth, or so I'm told. I have not been there myself.

According to the no boundary proposal, the universe would have expanded in a smooth way from a single point. As it expanded, it would have borrowed energy from the gravitational field, to create matter. As any economist could have predicted, the result of all that borrowing, was inflation. The universe expanded and borrowed at an ever-increasing rate. Fortunately, the debt of gravitational energy will not have to be repaid until the end of the universe.

Eventually, the period of inflation would have ended, and the universe would have settled down to a stage of more moderate growth or expansion. However, inflation would have left its mark on the universe. The universe would have been almost completely smooth, but with very slight irregularities. These irregularities are so little, only one part in a hundred thousand, that for years people looked for them in vain. But in 1992, the Cosmic Background Explorer satellite, COBE, found these irregularities in the microwave background radiation. It was an historic moment. We saw back to the origin of the universe. The form of the fluctuations in the microwave background agree closely with the predictions of the no boundary proposal. These very slight irregularities in the universe would have caused some regions to have expanded less fast than others. Eventually, they would have stopped expanding, and would have collapsed in on themselves, to form stars and galaxies. Thus the no boundary proposal can explain all the rich and varied structure, of the world we live in. What does the no boundary proposal predict for the future of the universe? Because it requires that the universe is finite in space, as well as in imaginary time, it implies that the universe will re-collapse eventually. However, it will not re-collapse for a very long time, much longer than the 15 billion years it has already been expanding. So, you will have time to sell your government bonds, before the end of the universe is nigh. Quite what you invest in then, I don't know.

Originally, I thought that the collapse, would be the time reverse of the expansion. This would have meant that the arrow of time would have pointed the other way in the contracting phase. People would have gotten younger, as the universe got smaller. Eventually, they would have disappeared back into the womb.

However, I now realise I was wrong, as these solutions show. The collapse is not the time reverse of the expansion. The expansion will start with an inflationary phase, but the collapse will not in general end with an anti inflationary phase. Moreover, the small departures from uniform density will continue to grow in the contracting phase. The universe will get more and more lumpy and irregular, as it gets smaller, and disorder will increase. This means that the arrow of time will not reverse. People will continue to get older, even after the universe has begun to contract. So it is no good waiting until the universe re-collapses, to return to your youth. You would be a bit past it, anyway, by then.

The conclusion of this lecture is that the universe has not existed forever. Rather, the universe, and time itself, had a beginning in the Big Bang, about 15 billion years ago. The beginning of real time, would have been a singularity, at which the laws of physics would have broken down. Nevertheless, the way the universe began would have been determined by the laws of physics, if the universe satisfied the no boundary condition. This says that in the imaginary time direction, space-time is finite in extent, but doesn't have any boundary or edge. The predictions of the no boundary proposal seem to agree with observation. The no boundary hypothesis also predicts that the universe will eventually collapse again. However, the contracting phase, will not have the opposite arrow of time, to the expanding phase. So we will keep on getting older, and we won't return to our youth. Because time is not going to go backwards, I think I better stop now.

Life in the Universe

In this talk, I would like to speculate a little, on the development of life in the universe, and in particular, the development of intelligent life. I shall take this to include the human race, even though much of its behaviour throughout history, has been pretty stupid, and not calculated to aid the survival of the species. Two questions I shall discuss are, 'What is the probability of life existing elsewhere in the universe?' and, 'How may life develop in the future?'

It is a matter of common experience, that things get more disordered and chaotic with time. This observation can be elevated to the status of a law, the so-called Second Law of Thermodynamics. This says that the total amount of disorder, or entropy, in the universe, always increases with time. However, the Law refers only to the total amount of disorder. The order in one body can increase, provided that the amount of disorder in its surroundings increases by a greater amount. This is what happens in a living being. One can define Life to be an ordered system that can sustain itself against the tendency to disorder, and can reproduce itself. That is, it can make similar, but independent, ordered systems. To do these things, the system must convert energy in some ordered form, like food, sunlight, or electric power, into disordered energy, in the form of heat. In this way, the system can satisfy the requirement that the total amount of disorder increases, while, at the same time, increasing the order in itself and its offspring. A living being usually has two elements: a set of instructions that tell the system how to sustain and reproduce itself, and a mechanism to carry out the instructions. In biology, these two parts are called genes and metabolism. But it is worth emphasising that there need be nothing biological about them. For example, a computer virus is a program that will make copies of itself in the memory of a computer, and will transfer itself to other computers. Thus it fits the definition of a living system, that I have given. Like a biological virus, it is a rather degenerate form, because it contains only instructions or genes, and doesn't have any metabolism of its own. Instead, it reprograms the metabolism of the host computer, or cell. Some people have questioned whether viruses should count as life, because they are parasites, and can not exist independently of their hosts. But then most forms of life, ourselves included, are parasites, in that they feed off and depend for their survival on other forms of life. I think computer viruses should count as life. Maybe it says something about human nature, that the only form of life we have created so far is purely destructive. Talk about creating life in our own image. I shall return to electronic forms of life later on.

What we normally think of as 'life' is based on chains of carbon atoms, with a few other atoms, such as nitrogen or phosphorous. One can speculate that one might have life with some other chemical basis, such as silicon, but carbon seems the most favourable case, because it has the richest chemistry. That carbon atoms should exist at all, with the properties that they have, requires a fine adjustment of physical constants, such as the QCD scale, the electric charge, and even the dimension of space-time. If these constants had significantly different values, either the nucleus of the carbon atom would not be stable, or the electrons would collapse in on the nucleus. At first sight, it seems remarkable that the universe is so finely tuned. Maybe this is evidence, that the universe was specially designed to produce the human race. However, one has to be careful about such arguments, because of what is known as the Anthropic Principle. This is based on the self-evident truth, that if the universe had not been suitable for life, we wouldn't be asking why it is so finely adjusted. One can apply the Anthropic Principle, in either its Strong, or Weak, versions. For the Strong Anthropic Principle, one supposes that there are many different universes, each with different values of the physical constants. In a small number, the values will allow the existence of objects like carbon atoms, which can act as the building blocks of living systems. Since we must live in one of these universes, we should not be surprised that the physical constants are finely tuned. If they weren't, we wouldn't be here. The strong form of the Anthropic Principle is not very satisfactory. What operational meaning can one give to the existence of all those other universes? And if they are separate from our own universe, how can what happens in them, affect our universe. Instead, I shall adopt what is known as the Weak Anthropic Principle. That is, I shall take the values of the physical constants, as given. But I shall see what conclusions can be drawn, from the fact that life exists on this planet, at this stage in the history of the universe.

There was no carbon, when the universe began in the Big Bang, about 15 billion years ago. It was so hot, that all the matter would have been in the form of particles, called protons and neutrons. There would initially have been equal numbers of protons and neutrons. However, as the universe expanded, it would have cooled. About a minute after the Big Bang, the temperature would have fallen to about a billion degrees, about a hundred times the temperature in the Sun. At this temperature, the neutrons will start to decay into more protons. If this had been all that happened, all the matter in the universe would have ended up as the simplest element, hydrogen, whose nucleus consists of a single proton. However, some of the neutrons collided with protons, and stuck together to form the next simplest element, helium, whose nucleus consists of two protons and two neutrons. But no heavier elements, like carbon or oxygen, would have been formed in the early universe. It is difficult to imagine that one could build a living system, out of just hydrogen and helium, and anyway the early universe was still far too hot for atoms to combine into molecules.

The universe would have continued to expand, and cool. But some regions would have had slightly higher densities than others. The gravitational attraction of the extra matter in those regions, would slow down their expansion, and eventually stop it. Instead, they would collapse to form galaxies and stars, starting from about two billion years after the Big Bang. Some of the early stars would have been more massive than our Sun. They would have been hotter than the Sun, and would have burnt the original hydrogen and helium, into heavier elements, such as carbon, oxygen, and iron. This could have taken only a few hundred million years. After that, some of the stars would have exploded as supernovas, and scattered the heavy elements back into space, to form the raw material for later generations of stars.

Other stars are too far away, for us to be able to see directly, if they have planets going round them. But certain stars, called pulsars, give off regular pulses of radio waves. We observe a slight variation in the rate of some pulsars, and this is interpreted as indicating that they are being disturbed, by having Earth sized planets going round them. Planets going round pulsars are unlikely to have life, because any living beings would have been killed, in the supernova explosion that led to the star becoming a pulsar. But, the fact that several pulsars are observed to have planets suggests that a reasonable fraction of the hundred billion stars in our galaxy may also have planets. The necessary planetary conditions for our form of life may therefore have existed from about four billion years after the Big Bang.

Our solar system was formed about four and a half billion years ago, or about ten billion years after the Big Bang, from gas contaminated with the remains of earlier stars. The Earth was formed largely out of the heavier elements, including carbon and oxygen. Somehow, some of these atoms came to be arranged in the form of molecules of DNA. This has the famous double helix form, discovered by Crick and Watson, in a hut on the New Museum site in Cambridge. Linking the two chains in the helix, are pairs of nucleic acids. There are four types of nucleic acid, adenine, cytosine, guanine, and thiamine. I'm afraid my speech synthesiser is not very good, at pronouncing their names. Obviously, it was not designed for molecular biologists. An adenine on one chain is always matched with a thiamine on the other chain, and a guanine with a cytosine. Thus the sequence of nucleic acids on one chain defines a unique, complementary sequence, on the other chain. The two chains can then separate and each act as templates to build further chains. Thus DNA molecules can reproduce the genetic information, coded in their sequences of nucleic acids. Sections of the sequence can also be used to make proteins and other chemicals, which can carry out the instructions, coded in the sequence, and assemble the raw material for DNA to reproduce itself.

We do not know how DNA molecules first appeared. The chances against a DNA molecule arising by random fluctuations are very small. Some people have therefore suggested that life came to Earth from elsewhere, and that there are seeds of life floating round in the galaxy. However, it seems unlikely that DNA could survive for long in the radiation in space. And even if it could, it would not really help explain the origin of life, because the time available since the formation of carbon is only just over double the age of the Earth.

One possibility is that the formation of something like DNA, which could reproduce itself, is extremely unlikely. However, in a universe with a very large, or infinite, number of stars, one would expect it to occur in a few stellar systems, but they would be very widely separated. The fact that life happened to occur on Earth, is not however surprising or unlikely. It is just an application of the Weak Anthropic Principle: if life had appeared instead on another planet, we would be asking why it had occurred there.

If the appearance of life on a given planet was very unlikely, one might have expected it to take a long time. More precisely, one might have expected life to appear just in time for the subsequent evolution to intelligent beings, like us, to have occurred before the cut off, provided by the life time of the Sun. This is about ten billion years, after which the Sun will swell up and engulf the Earth. An intelligent form of life, might have mastered space travel, and be able to escape to another star. But otherwise, life on Earth would be doomed.

There is fossil evidence, that there was some form of life on Earth, about three and a half billion years ago. This may have been only 500 million years after the Earth became stable and cool enough, for life to develop. But life could have taken 7 billion years to develop, and still have left time to evolve to beings like us, who could ask about the origin of life. If the probability of life developing on a given planet, is very small, why did it happen on Earth, in about one 14th of the time available.

The early appearance of life on Earth suggests that there's a good chance of the spontaneous generation of life, in suitable conditions. Maybe there was some simpler form of organisation, which built up DNA. Once DNA appeared, it would have been so successful, that it might have completely replaced the earlier forms. We don't know what these earlier forms would have been. One possibility is RNA. This is like DNA, but rather simpler, and without the double helix structure. Short lengths of RNA, could reproduce themselves like DNA, and might eventually build up to DNA. One cannot make nucleic acids in the laboratory, from non-living material, let alone RNA. But given 500 million years, and oceans covering most of the Earth, there might be a reasonable probability of RNA, being made by chance.

As DNA reproduced itself, there would have been random errors. Many of these errors would have been harmful, and would have died out. Some would have been neutral. That is they would not have affected the function of the gene. Such errors would contribute to a gradual genetic drift, which seems to occur in all populations. And a few errors would have been favourable to the survival of the species. These would have been chosen by Darwinian natural selection.

The process of biological evolution was very slow at first. It took two and a half billion years, to evolve from the earliest cells to multi-cell animals, and another billion years to evolve through fish and reptiles, to mammals. But then evolution seemed to have speeded up. It only took about a hundred million years, to develop from the early mammals to us. The reason is, fish contain most of the important human organs, and mammals, essentially all of them. All that was required to evolve from early mammals, like lemurs, to humans, was a bit of fine-tuning.

But with the human race, evolution reached a critical stage, comparable in importance with the development of DNA. This was the development of language, and particularly written language. It meant that information can be passed on, from generation to generation, other than genetically, through DNA. There has been no detectable change in human DNA, brought about by biological evolution, in the ten thousand years of recorded history. But the amount of knowledge handed on from generation to generation has grown enormously. The DNA in human beings contains about three billion nucleic acids. However, much of the information coded in this sequence, is redundant, or is inactive. So the total amount of useful information in our genes, is probably something like a hundred million bits. One bit of information is the answer to a yes no question. By contrast, a paperback novel might contain two million bits of information. So a human is equivalent to 50 Mills and Boon romances. A major national library can contain about five million books, or about ten trillion bits. So the amount of information handed down in books, is a hundred thousand times as much as in DNA.

Even more important, is the fact that the information in books, can be changed, and updated, much more rapidly. It has taken us several million years to evolve from the apes. During that time, the useful information in our DNA, has probably changed by only a few million bits. So the rate of biological evolution in humans, is about a bit a year. By contrast, there are about 50,000 new books published in the English language each year, containing of the order of a hundred billion bits of information. Of course, the great majority of this information is garbage, and no use to any form of life. But, even so, the rate at which useful information can be added is millions, if not billions, higher than with DNA.

This has meant that we have entered a new phase of evolution. At first, evolution proceeded by natural selection, from random mutations. This Darwinian phase, lasted about three and a half billion years, and produced us, beings who developed language, to exchange information. But in the last ten thousand years or so, we have been in what might be called, an external transmission phase. In this, the internal record of information, handed down to succeeding generations in DNA, has not changed significantly. But the external record, in books, and other long lasting forms of storage, has grown enormously. Some people would use the term, evolution, only for the internally transmitted genetic material, and would object to it being applied to information handed down externally. But I think that is too narrow a view. We are more than just our genes. We may be no stronger, or inherently more intelligent, than our cave man ancestors. But what distinguishes us from them, is the knowledge that we have accumulated over the last ten thousand years, and particularly, over the last three hundred. I think it is legitimate to take a broader view, and include externally transmitted information, as well as DNA, in the evolution of the human race.

The time scale for evolution, in the external transmission period, is the time scale for accumulation of information. This used to be hundreds, or even thousands, of years. But now this time scale has shrunk to about 50 years, or less. On the other hand, the brains with which we process this information have evolved only on the Darwinian time scale, of hundreds of thousands of years. This is beginning to cause problems. In the 18th century, there was said to be a man who had read every book written. But nowadays, if you read one book a day, it would take you about 15,000 years to read through the books in a national Library. By which time, many more books would have been written.

This has meant that no one person can be the master of more than a small corner of human knowledge. People have to specialise, in narrower and narrower fields. This is likely to be a major limitation in the future. We certainly cannot continue, for long, with the exponential rate of growth of knowledge that we have had in the last three hundred years. An even greater limitation and danger for future generations, is that we still have the instincts, and in particular, the aggressive impulses, that we had in cave man days. Aggression, in the form of subjugating or killing other men, and taking their women and food, has had definite survival advantage, up to the present time. But now it could destroy the entire human race, and much of the rest of life on Earth. A nuclear war, is still the most immediate danger, but there are others, such as the release of a genetically engineered virus. Or the green house effect becoming unstable.

There is no time, to wait for Darwinian evolution, to make us more intelligent, and better natured. But we are now entering a new phase, of what might be called, self designed evolution, in which we will be able to change and improve our DNA. There is a project now on, to map the entire sequence of human DNA. It will cost a few billion dollars, but that is chicken feed, for a project of this importance. Once we have read the book of life, we will start writing in corrections. At first, these changes will be confined to the repair of genetic defects, like cystic fibrosis, and muscular dystrophy. These are controlled by single genes, and so are fairly easy to identify, and correct. Other qualities, such as intelligence, are probably controlled by a large number of genes. It will be much more difficult to find them, and work out the relations between them. Nevertheless, I am sure that during the next century, people will discover how to modify both intelligence, and instincts like aggression.

Laws will be passed, against genetic engineering with humans. But some people won't be able to resist the temptation, to improve human characteristics, such as size of memory, resistance to disease, and length of life. Once such super humans appear, there are going to be major political problems, with the unimproved humans, who won't be able to compete. Presumably, they will die out, or become unimportant. Instead, there will be a race of self-designing beings, who are improving themselves at an ever-increasing rate.

If this race manages to redesign itself, to reduce or eliminate the risk of self-destruction, it will probably spread out, and colonise other planets and stars. However, long distance space travel, will be difficult for chemically based life forms, like DNA. The natural lifetime for such beings is short, compared to the travel time. According to the theory of relativity, nothing can travel faster than light. So the round trip to the nearest star would take at least 8 years, and to the centre of the galaxy, about a hundred thousand years. In science fiction, they overcome this difficulty, by space warps, or travel through extra dimensions. But I don't think these will ever be possible, no matter how intelligent life becomes. In the theory of relativity, if one can travel faster than light, one can also travel back in time. This would lead to problems with people going back, and changing the past. One would also expect to have seen large numbers of tourists from the future, curious to look at our quaint, old-fashioned ways.

It might be possible to use genetic engineering, to make DNA based life survive indefinitely, or at least for a hundred thousand years. But an easier way, which is almost within our capabilities already, would be to send machines. These could be designed to last long enough for interstellar travel. When they arrived at a new star, they could land on a suitable planet, and mine material to produce more machines, which could be sent on to yet more stars. These machines would be a new form of life, based on mechanical and electronic components, rather than macromolecules. They could eventually replace DNA based life, just as DNA may have replaced an earlier form of life.

This mechanical life could also be self-designing. Thus it seems that the external transmission period of evolution, will have been just a very short interlude, between the Darwinian phase, and a biological, or mechanical, self design phase. This is shown on this next diagram, which is not to scale, because there's no way one can show a period of ten thousand years, on the same scale as billions of years. How long the self-design phase will last is open to question. It may be unstable, and life may destroy itself, or get into a dead end. If it does not, it should be able to survive the death of the Sun, in about 5 billion years, by moving to planets around other stars. Most stars will have burnt out in another 15 billion years or so, and the universe will be approaching a state of complete disorder, according to the Second Law of Thermodynamics. But Freeman Dyson has shown that, despite this, life could adapt to the ever-decreasing supply of ordered energy, and therefore could, in principle, continue forever.

What are the chances that we will encounter some alien form of life, as we explore the galaxy. If the argument about the time scale for the appearance of life on Earth is correct, there ought to be many other stars, whose planets have life on them. Some of these stellar systems could have formed 5 billion years before the Earth. So why is the galaxy not crawling with self designing mechanical or biological life forms? Why hasn't the Earth been visited, and even colonised. I discount suggestions that UFO's contain beings from outer space. I think any visits by aliens, would be much more obvious, and probably also, much more unpleasant.

What is the explanation of why we have not been visited? One possibility is that the argument, about the appearance of life on Earth, is wrong. Maybe the probability of life spontaneously appearing is so low, that Earth is the only planet in the galaxy, or in the observable universe, in which it happened. Another possibility is that there was a reasonable probability of forming self reproducing systems, like cells, but that most of these forms of life did not evolve intelligence. We are used to thinking of intelligent life, as an inevitable consequence of evolution. But the Anthropic Principle should warn us to be wary of such arguments. It is more likely that evolution is a random process, with intelligence as only one of a large number of possible outcomes. It is not clear that intelligence has any long-term survival value. Bacteria, and other single cell organisms, will live on, if all other life on Earth is wiped out by our actions. There is support for the view that intelligence, was an unlikely development for life on Earth, from the chronology of evolution. It took a very long time, two and a half billion years, to go from single cells to multi-cell beings, which are a necessary precursor to intelligence. This is a good fraction of the total time available, before the Sun blows up. So it would be consistent with the hypothesis, that the probability for life to develop intelligence, is low. In this case, we might expect to find many other life forms in the galaxy, but we are unlikely to find intelligent life. Another way, in which life could fail to develop to an intelligent stage, would be if an asteroid or comet were to collide with the planet. We have just observed the collision of a comet, Schumacher-Levi, with Jupiter. It produced a series of enormous fireballs. It is thought the collision of a rather smaller body with the Earth, about 70 million years ago, was responsible for the extinction of the dinosaurs. A few small early mammals survived, but anything as large as a human, would have almost certainly been wiped out. It is difficult to say how often such collisions occur, but a reasonable guess might be every twenty million years, on average. If this figure is correct, it would mean that intelligent life on Earth has developed only because of the lucky chance that there have been no major collisions in the last 70 million years. Other planets in the galaxy, on which life has developed, may not have had a long enough collision free period to evolve intelligent beings.

A third possibility is that there is a reasonable probability for life to form, and to evolve to intelligent beings, in the external transmission phase. But at that point, the system becomes unstable, and the intelligent life destroys itself. This would be a very pessimistic conclusion. I very much hope it isn't true. I prefer a fourth possibility: there are other forms of intelligent life out there, but that we have been overlooked. There used to be a project called SETI, the search for extra-terrestrial intelligence. It involved scanning the radio frequencies, to see if we could pick up signals from alien civilisations. I thought this project was worth supporting, though it was cancelled due to a lack of funds. But we should have been wary of answering back, until we have develop a bit further. Meeting a more advanced civilisation, at our present stage, might be a bit like the original inhabitants of America meeting Columbus. I don't think they were better off for it.

That is all I have to say. Thank you for listening

Transcript of Stephen Hawking's second Reith lecture

Lecture broadcast on 02.02.2016

With annotations by BBC Science Editor David Shukman

In my previous lecture I left you on a cliffhanger: a paradox about the nature of black holes, the incredibly dense objects created by the collapse of stars. One theory suggested that black holes with identical qualities could be formed from an infinite number of different types of stars. Another suggested that the number could be finite. This is a problem of information, that is the idea that every particle and every force in the universe contains information, an implicit answer to a yes-no question.

Because black holes have no hair, as the scientist John Wheeler put it, one can't tell from the outside what is inside a black hole, apart from its mass, electric charge, and rotation. This means that a black hole contains a lot of information that is hidden from the outside world. If the amount of hidden information inside a black hole depends on the size of the hole, one would expect from general principles that the black hole would have a temperature, and would glow like a piece of hot metal. But that was impossible, because as everyone knew, nothing could get out of a black hole. Or so it was thought.

This problem remained until early in 1974, when I was investigating what the behaviour of matter in the vicinity of a black hole would be, according to quantum mechanics.

DS: Quantum mechanics is the science of the extremely small and it seeks to explain the behaviour of the tiniest particles. These do not act according to the laws that govern the movements of much bigger objects like planets, laws that were first framed by Isaac Newton. Using the science of the very small to study the very large was one of Stephen Hawking's pioneering achievements.

To my great surprise I found that the black hole seemed to emit particles at a steady rate. Like everyone else at that time, I accepted the dictum that a black hole could not emit anything. I therefore put quite a lot of effort into trying to get rid of this embarrassing effect. But the more I thought about it, the more it refused to go away, so that in the end I had to accept it. What finally convinced me it was a real physical process was that the outgoing particles have a spectrum that is precisely thermal. My calculations predicted that a black hole creates and emits particles and radiation, just as if it were an ordinary hot body, with a temperature that is proportional to the surface gravity, and inversely proportional to the mass.

DS: These calculations were the first to show that a black hole need not be a one-way street to a dead end. No surprise, the emissions suggested by the theory became known as Hawking Radiation.

Since that time, the mathematical evidence that black holes emit thermal radiation has been confirmed by a number of other people with various different approaches. One way to understand the emission is as follows. Quantum mechanics implies that the whole of space is pairs of virtual and anti particles, filled with pairs of virtual particles and antiparticles, that are constantly materializing in pairs, separating, and then coming together again, and annihilating each other.

DS: This concept hinges on the idea that a vacuum is never totally empty. According to the uncertainty principle of quantum mechanics, there is always the chance that particles may come into existence, however briefly. And this would always involve pairs of particles, with opposite characteristics, appearing and disappearing.

These particles are called virtual because unlike real particles they cannot be observed directly with a particle detector. Their indirect effects can nonetheless be measured, and their existence has been confirmed by a small shift, called the Lamb shift, which they produce in the spectrum energy of light from excited hydrogen atoms. Now in the presence of a black hole, one member of a pair of virtual particles may fall into the hole, leaving the other member without a partner with which to annihilate. The forsaken particle or antiparticle may fall into the black hole after its partner, but it may also escape to infinity, where it appears to be radiation emitted by the black hole.

DS: The key here is that the formation and disappearance of these particles normally passes unnoticed. But if the process happens right on the edge of a black hole, one of the pair may get dragged in while the other is not. The particle that escapes would then look as if it’s being spat out by the black hole.

A black hole of the mass of the sun, would leak particles at such a slow rate, it would be impossible to detect. However, there could be much smaller mini black holes with the mass of say, a mountain. A mountain-sized black hole would give off x-rays and gamma rays, at a rate of about ten million megawatts, enough to power the world's electricity supply. It wouldn't be easy however, to harness a mini black hole. You couldn't keep it in a power station, because it would drop through the floor and end up at the centre of the Earth. If we had such a black hole, about the only way to keep hold of it would be to have it in orbit around the Earth.

People have searched for mini black holes of this mass, but have so far not found any. This is a pity, because if they had I would have got a Nobel Prize. Another possibility, however, is that we might be able to create micro black holes in the extra dimensions of space time.

DS: By ‘extra dimensions’, he means something beyond the three dimensions that we are all familiar with in our everyday lives, plus the fourth dimension of time. The idea arose as part of an effort to explain why gravity is so much weaker than other forces such as magnetism – maybe it’s also having to operate in parallel dimensions.

According to some theories, the universe we experience is just a four dimensional surface in a ten or eleven dimensional space. The movie Interstellar gives some idea of what this is like. We wouldn't see these extra dimensions because light wouldn't propagate through them but only through the four dimensions of our universe. Gravity, however, would affect the extra dimensions and would be much stronger than in our universe. This would make it much easier to form a little black hole in the extra dimensions. It might be possible to observe this at the LHC, the Large Hadron Collider, at CERN in Switzerland. This consists of a circular tunnel, 27 kilometres long. Two beams of particles travel round this tunnel in opposite directions, and are made to collide. Some of the collisions might create micro black holes. These would radiate particles in a pattern that would be easy to recognize. So I might get a Nobel Prize after all.

DS: The Nobel Prize in Physics is awarded when a theory is “tested by time” which in practice means confirmation by hard evidence. For example, Peter Higgs was among scientists who, back in the 1960s, suggested the existence of a particle that would give other particles their mass. Nearly 50 years later, two different detectors at the Large Hadron Collider spotted signs of what had become known as the Higgs Boson. It was a triumph of science and engineering, of clever theory and hard-won evidence. And Peter Higgs and Francois Englert, a Belgian scientist, were jointly awarded the prize. No physical proof has yet been found of Hawking Radiation.

As particles escape from a black hole, the hole will lose mass, and shrink. This will increase the rate of emission of particles. Eventually, the black hole will lose all its mass, and disappear. What then happens to all the particles and unlucky astronauts that fell into the black hole? They can't just re-emerge when the black hole disappears. It appears that the information about what fell in is lost, apart from the total amount of mass, and the amount of rotation. But if information is lost, this raises a serious problem that strikes at the heart of our understanding of science.

For more than 200 years, we have believed in scientific determinism, that is, that the laws of science determine the evolution of the universe. This was formulated by Pierre-Simon Laplace, who said that if we know the state of the universe at one time, the laws of science will determine it at all future and past times. Napoleon is said to have asked Laplace how God fitted into this picture. Laplace replied, “Sire, I have not needed that hypothesis.” I don't think that Laplace was claiming that God didn't exist. It is just that he doesn't intervene to break the laws of science. That must be the position of every scientist. A scientific law is not a scientific law if it only holds when some supernatural being decides to let things run and not intervene.

In Laplace's determinism, one needed to know the positions and speeds of all particles at one time, in order to predict the future. But there's the uncertainty relationship, discovered by Walter Heisenberg in 1923, which lies at the heart of quantum mechanics.

This holds that the more accurately you know the positions of particles, the less accurately you can know their speeds, and vice versa. In other words, you can't know both the positions and the speeds accurately. How then can you predict the future accurately? The answer is that although one can't predict the positions and speeds separately, one can predict what is called the quantum state. This is something from which both positions and speeds can be calculated to a certain degree of accuracy. We would still expect the universe to be deterministic, in the sense that if we knew the quantum state of the universe at one time, the laws of science should enable us to predict it at any other time.

DS: What began as an explanation of what happens at an event horizon has deepened into an exploration of some of the most important philosophies in science - from the clockwork world of

Newton to the laws of Laplace to the uncertainties of Heisenberg – and where they are challenged by the mystery of black holes. Essentially, information entering a black hole should be destroyed, according to Einstein's Theory of General Relativity while quantum theory says it cannot be broken down, and this remains an unresolved question.

If information were lost in black holes, we wouldn't be able to predict the future, because a black hole could emit any collection of particles. It could emit a working television set, or a leather-bound volume of the complete works of Shakespeare, though the chance of such exotic emissions is very low. It might seem that it wouldn't matter very much if we couldn't predict what comes out of black holes. There aren't any black holes near us. But it is a matter of principle. If determinism, the predictability of the universe, breaks down with black holes, it could break down in other situations. Even worse, if determinism breaks down, we can't be sure of our past history either. The history books and our memories could just be illusions. It is the past that tells us who we are. Without it, we lose our identity.

It was therefore very important to determine whether information really was lost in black holes, or whether in principle, it could be recovered. Many scientists felt that information should not be lost, but no one could suggest a mechanism by which it could be preserved. The arguments went on for years. Finally, I found what I think is the answer. It depends on the idea of Richard Feynman, that there isn't a single history, but many different possible histories, each with their own probability. In this case, there are two kinds of history. In one, there is a black hole, into which particles can fall, but in the other kind there is no black hole.

The point is that from the outside, one can't be certain whether there is a black hole or not. So there is always a chance that there isn't a black hole. This possibility is enough to preserve the information, but the information is not returned in a very useful form. It is like burning an encyclopaedia. Information is not lost if you keep all the smoke and ashes, but it is difficult to read. The scientist Kip Thorne and I had a bet with another physicist, John Preskill, that information would be lost in black holes. When I discovered how information could be preserved, I conceded the bet. I gave John Preskill an encyclopaedia. Maybe I should have just given him the ashes.

DS: In theory, and with a purely deterministic view of the universe, you could burn an encyclopaedia and then reconstitute it if you knew the characteristics and position of every atom making up every molecule of ink in every letter and kept track of them all at all times.

Currently I'm working with my Cambridge colleague Malcolm Perry and Andrew Strominger from Harvard on a new theory based on a mathematical idea called supertranslations to explain the mechanism by which information is returned out of the black hole. The information is encoded on the horizon of the black hole. Watch this space.

DS: Since the Reith Lectures were recorded, Prof Hawking and his colleagues have published a paper which makes a mathematical case that information can be stored in the event horizon. The theory hinges on information being transformed into a two-dimensional hologram in a process known as supertranslations. The paper, titled Soft Hair on Black Holes, offers a highly revealing glimpse into the esoteric language of this field and the challenge that scientists face in trying to explain it.

What does this tell us about whether it is possible to fall in a black hole, and come out in another universe? The existence of alternative histories with black holes suggests this might be possible. The hole would need to be large, and if it was rotating, it might have a passage to another universe. But you couldn't come back to our universe. So although I'm keen on space flight, I'm not going to try that.

DS: If black holes are rotating, then their heart may not consist of a singularity in the sense of an infinitely dense point. Instead, there may be a singularity in the form of a ring. And that leads to speculation about the possibility of not only falling into a black hole but also travelling through one. This would mean leaving the universe as we know it. And Stephen Hawking concludes with a tantalising thought: that there may something on the other side.

The message of this lecture is that black holes ain't as black as they are painted. They are not the eternal prisons they were once thought. Things can get out of a black hole, both to the outside, and possibly to another universe. So if you feel you are in a black hole, don't give up. There's a way out. Thank you very much.

Transcript of audience Q and A after the second lecture

SUE LAWLEY: Professor Hawking, thank you very much indeed. So we've been taken on a trip to the outer regions of the universe, to the brink of human understanding and beyond. Listeners have sent in hundreds of questions for the professor and some of them are here with us now in the lecture theatre of the Royal Institution in London to put their questions in person. Can we have our first questioner, please? She's Marie Griffiths who comes from Godalming in Surrey, a civil servant at the Department for Education and has always been interested in physics. Your question, please, Marie?

MARIE GRIFFITHS: Did the Big Bang start just one universe or all the multiverses? SUE LAWLEY: Stephen?

STEPHEN HAWKING: Some theories about the Big Bang allow for the creation of a very large and complex universe, maybe even many universes. However, even if there were other universes, we wouldn't know about them. Our connected component of space time is all we can know.

SUE LAWLEY: It's all we can know, Marie. And it's quite enough, by the sound of it. Let's have our next question – a question from John Brookmyre from Middlesbrough who describes himself as an ordinary working bloke and a lifelong learner. He couldn't unfortunately get here today, but let me put his question to you for him, Stephen. If you were a time lord, what moment in time would interest you and why?

STEPHEN HAWKING: I would like to meet Galileo. He was the first modern scientist, who realized the importance of observation. Galileo was the first person to challenge the received wisdom that the ancient Greeks, and Aristotle in particular, were the ultimate authority in science. Galileo pointed out that simple observations, like dropping weights from a height, show things do not work the way Aristotle said. This must have been seen by many people, but they had put it down to imperfect observations, or other reasons. But Galileo said the ancients were actually wrong and started to work out the correct laws from the observations. That makes him the father of modern science. He followed his nose, and was a bit of a rebel. (laughter)

SUE LAWLEY: A rebel who was forced to recant, of course. Right I'm going to come to Dara O'Briain over here on the right. Dara, the entertainer and science graduate. He studied pure mathematics and theoretical physics at University College Dublin in preparation for his career as a stand-up comic. (laughter) So you're an expert, are you Dara, on both physics and humour?

DARA O'BRIAIN: Yes, yeah, we overlap in some ways. Given that Stephen has appeared twice in The Simpsons, he has a more successful comedy career than I do. (laughter)

SUE LAWLEY: But he was your boyhood hero, wasn't he?

DARA O'BRIAIN: There was a huge … Yes I remember receiving a copy of A Brief History of Time for my Christmas when I was about 16. I had the pleasure this year of meeting him and having it autographed as it were and spending some time with Stephen this year. It was an honour.

SUE LAWLEY: Okay ask him another question.

DARA O'BRIAIN: Well actually given the chance, I turned the opportunity of this question over to some physicists I know – in particular Jim Al-Khalili. Professor Jim Al-Khalili wanted to ask a question from within the scientific community. As he said, most of the people in the physics community would indeed see the confirmation of Hawking radiation, which Professor Hawking invented in 1974, as being worthy of a Nobel Prize since it would have been the first theoretical prediction that required both quantum mechanics and relativity. Does Professor Hawking believe that Hawking radiation will be observed in his lifetime? And if it is observed, where does he think this experimental evidence will come from?

STEPHEN HAWKING: I am resigned to the fact that I won't see proof of Hawking radiation directly, though there are solid state analogues of black holes and cyclotron effects that the Nobel committee might accept as proof. (laughter) But there's another kind of Hawking radiation coming from the cosmological event horizon of the early inflationary universe. I'm now studying whether one might detect Hawking radiation in primordial gravitational waves. So I might get a Nobel Prize after all.

SUE LAWLEY: (laughter) A new kind of Hawking radiation then from light years earlier. Does that excite you Dara?

DARA O'BRIAIN: It does say one thing, however – that the work that Professor Hawking's been doing, theoretically and has been doing??, has skipped so far ahead of what we can do experimentally that there will be for a long time people racing to keep up with this work.

SUE LAWLEY: So I dare say you think that, whatever happens, he should get the Nobel Prize, huh?

DARA O'BRIAIN: If it was done by public acclaim, if it was a phone vote, (laughter) but the Swedes are notoriously sticky about that kind of stuff. So yeah, but I do believe - yes.

SUE LAWLEY: Okay. Chris Cooke, a 25 year old product designer from Crawley in Sussex. Chris studied mechanical engineering, so he's always been interested in physics. In his spare time, he does stand-up comedy, Dara, "despite my introverted … (laughter) despite my introverted personality traits", he says. Chris, your question?

CHRIS COOKE: Do you feel that using a speech device to communicate has changed your personality in any way? As an introvert, has it made you more extroverted?

SUE LAWLEY: Stephen?

STEPHEN HAWKING: Well I am not sure I have ever been called an introvert before. (laughter) Just because I spend a lot of time thinking doesn't mean I don't like parties and getting into trouble. (laughter) I enjoy communicating and I enjoy giving popular lectures about science. My speech synthesizer has been very important for this, even though I ended up with an American accent. (laughter) Before I lost my voice, my speech was slurred, so only those close to me could understand, but with the computer voice I found I could talk to everyone without help. So it has allowed me to express my personality rather than changing it.

SUE LAWLEY: Thank you very much for that question. Another questioner, Patrick Donaghue. He's a set designer who lives and works in London. Your question, Patrick?

PATRICK DONAGUE: Professor Hawking, do you think the world will end naturally or will man destroy it first?

SUE LAWLEY: Professor Hawking, just a small question. (laughter)

STEPHEN HAWKING: We face a number of threats to our survival from nuclear war, catastrophic global warming, and genetically engineered viruses. The number is likely to increase in the future, with the development of new technologies, and new ways things can go wrong. Although the chance of a disaster to planet Earth in a given year may be quite low, it adds up over time, and becomes a near certainty in the next thousand or ten thousand years. By that time we should have spread out into space, and to other stars, so a disaster on Earth would not mean the end of the human race.

However, we will not establish selfsustaining colonies in space for at least the next hundred years, so we have to be very careful in this period. (laughter) Most of the threats we face come from the progress we have made in science and technology. We are not going to stop making progress, or reverse it, so we have to recognize the dangers and control them. I'm an optimist, and I believe we can.

SUE LAWLEY: Well I don’t know about the world, but we’re definitely running out of time. We’ve got one last question from Tara Struthers who’s originally from the Orkneys, which may account for her lifelong interest in astronomy. These days she works for a film production company.

TARA STRUTHERS: If you had to offer one piece of advice for future generations of scientists, namely physicists and cosmologists, what would it be?

STEPHEN HAWKING: Science is a great enterprise and I want to share my excitement and enthusiasm about its success. From my own perspective, it has been a glorious time to be alive and doing research in theoretical physics. There is nothing like the Eureka moment of discovering something that no one knew before. So my advice to young scientists is to be curious, and try to make sense of what you see. We live in a universe governed by rational laws that we can discover and understand. Despite recent triumphs, there are many new and deep mysteries that remain for you to solve. And keep a sense of wonder about our vast and complex universe and what makes it exist. But you also must remember that science and technology are changing our world dramatically, so it’s important to ensure that these changes are heading in the right directions. In a democratic society, this means that everyone needs to have a basic understanding of science to make informed decisions about the future. So communicate plainly what you are trying to do in science, and who knows, you might even end up understanding it yourself. (laughter)

SUE LAWLEY: And there we must end. Newton was once asked how he’d managed to understand so much about the laws of the universe and he answered: "by thinking of these things continually." Those of us who rely on others to do their thinking for them, are very glad that we have men like Stephen Hawking. His lectures will be available on the BBC Reith website where you’ll find recordings, transcripts and videos - an archive of all 67 series of Reith Lectures going back to 1948. For now, from the Royal Institution in London, our thanks to the BBC Reith Lecturer Professor Stephen Hawking. And goodbye.

Transcript of Stephen Hawking's first Reith lecture

Lecture broadcast 26.01.2016
With annotations by BBC Science Editor David Shukman

With appearances on comedy shows, books in the best-seller lists and the unforgettable image of a brilliant mind in an ailing body, Stephen Hawking has earned the title of the world's most famous scientist. His field has never been easy for a wider public to grasp: everything from the formation of the universe to those strange but dangerous features known as black holes. But his energy and humour, and his determination to reach a wider audience, have always produced an enthusiastic response. And that inevitably brings a lot more questions of the kind that people might find embarrassing to ask in public. So, as a guide for the interested but perplexed, I have added a few notes to the first of Stephen Hawking's BBC Reith Lectures.

My talk is on black holes. It is said that fact is sometimes stranger than fiction, and nowhere is that more true than in the case of black holes. Black holes are stranger than anything dreamed up by science fiction writers, but they are firmly matters of science fact. The scientific community was slow to realize that massive stars could collapse in on themselves, under their own gravity, and how the object left behind would behave. Albert Einstein even wrote a paper in 1939, claiming stars could not collapse under gravity, because matter could not be compressed beyond a certain point. Many scientists shared Einstein's gut feeling. The principal exception was the American scientist John Wheeler, who in many ways is the hero of the black hole story. In his work in the 1950s and '60s, he emphasized that many stars would eventually collapse, and the problems that posed for theoretical physics. He also foresaw many of the properties of the objects which collapsed stars become, that is, black holes.

DS: The phrase 'black hole' is simple enough but it's hard to imagine one out there in space. Think of a giant drain with water spiralling down into it. Once anything slips over the edge or 'event horizon', there is no return. Because black holes are so powerful, even light gets sucked in so we can't actually see them. But scientists know they exist because they rip apart stars and gas clouds that get too close to them.

During most of the life of a normal star, over many billions of years, it will support itself against its own gravity, by thermal pressure, caused by nuclear processes, which convert hydrogen into helium.

DS: NASA describes stars as rather like pressure-cookers. The explosive force of nuclear fusion inside them creates outward pressure which is constrained by gravity pulling everything inwards.

Eventually, however, the star will exhaust its nuclear fuel. The star will contract. In some cases, it may be able to support itself as a white dwarf star. However Subrahmanyan Chandrasekhar showed in 1930, that the maximum mass of a white dwarf star is about 1.4 times that of the Sun. A similar maximum mass was calculated by Soviet physicist, Lev Landau, for a star made entirely of neutrons.

DS: White dwarfs and neutron stars have exhausted their fuel so they have shrunk to become some of the densest objects in the universe. Most interesting to Stephen Hawking is what happens when the very biggest stars collapse in on themselves.

What would be the fate of those countless stars, with greater mass than a white dwarf or neutron star, when they had exhausted nuclear fuel? The problem was investigated by Robert Oppenheimer, of later atom bomb fame. In a couple of papers in 1939, with George Volkoff and Hartland Snyder, he showed that such a star could not be supported by pressure. And that if one neglected pressure, a uniform spherically systematic symmetric star would contract to a single point of infinite density. Such a point is called a singularity.

DS: A singularity is what you end up with when a giant star is compressed to an unimaginably small point. This concept has been a defining theme in Stephen Hawking's career. It refers to the end of a star but also something more fundamental: that a singularity was the starting-point for the formation of the entire universe. It was Hawking's mathematical work on this that earned him global recognition.

All our theories of space are formulated on the assumption that spacetime is smooth and nearly flat, so they break down at the singularity, where the curvature of space-time is infinite. In fact, it marks the end of time itself. That is what Einstein found so objectionable.

DS: Einstein's Theory of General Relativity says that objects distort the spacetime around them. Picture a bowling-ball lying on a trampoline, changing the shape of the material and causing smaller objects to slide towards it. This is how the effect of gravity is explained. But if the curves in spacetime become deeper and deeper, and eventually infinite, the usual rules of space and time no longer apply.

Then the war intervened. Most scientists, including Robert Oppenheimer, switched their attention to nuclear physics, and the issue of gravitational collapse was largely forgotten. Interest in the subject revived with the discovery of distant objects, called quasars.

DS: Quasars are the brightest objects in the universe, and possibly the most distant detected so far. The name is short for 'quasi-stellar radio sources' and they are believed to be discs of matter swirling around black holes.

The first quasar, 3C273, was discovered in 1963. Many other quasars were soon discovered. They were bright, despite being at great distances. Nuclear processes could not account for their energy output, because they release only a percent fraction of their rest mass as pure energy. The only alternative was gravitational energy, released by gravitational collapse.

Gravitational collapses of stars were re-discovered. It was clear that a uniform spherical star would contract to a point of infinite density, a singularity.

The Einstein equations can't be defined at a singularity. This means at this point of infinite density, one can't predict the future. This implies something strange could happen whenever a star collapsed. We wouldn't be affected by the breakdown of prediction, if the singularities are not naked, that is, they are not shielded from the outside.

DS: A 'naked' singularity is a theoretical scenario in which a star collapses but an event horizon does not form around it – so the singularity would be visible.

When John Wheeler introduced the term black hole in 1967, it replaced the earlier name, frozen star. Wheeler's coinage emphasized that the remnants of collapsed stars are of interest in their own right, independently of how they were formed. The new name caught on quickly. It suggested something dark and mysterious, But the French, being French, saw a more risque meaning. For years, they resisted the name trou noir, claiming it was obscene. But that was a bit like trying to stand against Le Week-end, and other Franglais. In the end, they had to give in. Who can resist a name that is such a winner?

From the outside, you can't tell what is inside a black hole. You can throw television sets, diamond rings, or even your worst enemies into a black hole, and all the black hole will remember is the total mass, and the state of rotation. John Wheeler is known for expressing this principle as "a black hole has no hair". To the French, this just confirmed their suspicions.

A black hole has a boundary, called the event horizon. It is where gravity is just strong enough to drag light back, and prevent it escaping. Because nothing can travel faster than light, everything else will get dragged back also. Falling through the event horizon is a bit like going over Niagara Falls in a canoe. If you are above the falls, you can get away if you paddle fast enough, but once you are over the edge, you are lost. There's no way back. As you get nearer the falls, the current gets faster. This means it pulls harder on the front of the canoe than the back. There's a danger that the canoe will be pulled apart. It is the same with black holes. If you fall towards a black hole feet first, gravity will pull harder on your feet than your head, because they are nearer the black hole.

The result is you will be stretched out longwise, and squashed in sideways. If the black hole has a mass of a few times our sun you would be torn apart, and made into spaghetti before you reached the horizon. However, if you fell into a much larger black hole, with a mass of a million times the sun, you would reach the horizon without difficulty. So, if you want to explore the inside of a black hole, make sure you choose a big one. There is a black hole with a mass of about four million times that of the sun, at the centre of our Milky Way galaxy.

DS: Scientists believe that there are huge black holes at the centre of virtually all galaxies – a remarkable thought, given how recently these features were confirmed in the first place.

Although you wouldn't notice anything particular as you fell into a black hole, someone watching you from a distance would never see you cross the event horizon. Instead, you would appear to slow down, and hover just outside. Your image would get dimmer and dimmer, and redder and redder, until you were effectively lost from sight. As far as the outside world is concerned, you would be lost for ever.

There was a dramatic advance in our understanding of these mysterious phenomena with a mathematical discovery in 1970. This was that the surface area of the event horizon, the boundary of a black hole, has the property that it always increases when additional matter or radiation falls into the black hole. These properties suggest that there is a resemblance between the area of the event horizon of a black hole, and conventional Newtonian physics, specifically the concept of entropy in thermodynamics. Entropy can be regarded as a measure of the disorder of a system, or equivalently, as a lack of knowledge of its precise state. The famous second law of thermodynamics says that entropy always increases with time. This discovery was the first hint of this crucial connection.

DS: Entropy means the tendency for anything that has order to become more disordered as time passes – so, for example, bricks neatly stacked to form a wall (low entropy) will eventually end up in an untidy heap of dust (high entropy). And this process is described by the second law of thermodynamics.

Although there is clearly a similarity between entropy and the area of the event horizon, it was not obvious to us how the area could be identified as the entropy of a black hole itself. What would be meant by the entropy of a black hole? The crucial suggestion was made in 1972 by Jacob Bekenstein, who was a graduate student at Princeton University, and then at the Hebrew University of Jerusalem. It goes like this. When a black hole is created by gravitational collapse, it rapidly settles down to a stationary state, which is characterized by only three parameters: the mass, the angular momentum, and the electric charge. Apart from these three properties, the black hole preserves no other details of the object that collapsed.

His theorem has implications for information, in the cosmologist's sense of information: the idea that every particle and every force in the universe has an implicit answer to a yes-no question.

DS: Information, in this context, means all the details of every particle and force associated with an object. And the more disordered something is – the higher its entropy - the more information is needed to describe it. As the physicist and broadcaster Jim Al-Khalili puts it, a well-shuffled pack of cards has higher entropy and therefore needs far more explanation, or information, than an unshuffled one.

The theorem implies that a large amount of information is lost in a gravitational collapse. For example, the final black-hole state is independent of whether the body that collapsed was composed of matter or antimatter, or whether it was spherical or highly irregular in shape. In other words, a black hole of a given mass, angular momentum and electric charge, could have been formed by the collapse of any one of a large number of different configurations of matter. So what appears to be the same black hole could be formed by the collapse of a large number of different types of star. Indeed, if quantum effects are neglected, the number of configurations would be infinite, since the black hole could have been formed by the collapse of a cloud of an indefinitely large number of particles, of indefinitely low mass. But could the number of configurations really be infinite?

The uncertainty principle of quantum mechanics implies that only particles with a wavelength smaller than that of the black hole itself could form a black hole. That means the wavelength would be limited: it could not be infinite.

DS: The uncertainty principle, conceived by the famous German physicist Werner Heisenberg, describes how we can never locate or predict the precise position of the smallest particles. So, at what is called the quantum scale, there is a fuzziness in nature, very unlike the more ordered universe described by Isaac Newton.

It therefore appears that the number of configurations that could form a black hole of a given mass, angular momentum and electric charge, although very large, may also be finite. Jacob Bekenstein suggested that from this finite number, one could interpret the entropy of a black hole. This would be a measure of the amount of information that was irretrievably lost during the collapse when a black hole was created.

The apparently fatal flaw in Bekenstein's suggestion was that if a black hole has a finite entropy that is proportional to the area of its event horizon, it also ought to have a finite temperature, which would be proportional to its surface gravity. This would imply that a black hole could be in equilibrium with thermal radiation, at some temperature other than zero. Yet according to classical concepts, no such equilibrium is possible, since the black hole would absorb any thermal radiation that fell on it, but by definition would not be able to emit anything in return. It cannot emit anything. It cannot emit heat.

DS: If information is lost, which is apparently what is happening in a black hole, there should be some release of energy - but that flies in the face of the theory that nothing comes out of black holes.

This is a paradox. And it's one which I am going to return to in my next lecture, when I'll be exploring how black holes challenge the most basic principle about the predictability of the universe, and the certainty of history, and asking what would happen if you ever got sucked into one. Thank you.

DS: So Stephen Hawking has taken us on a scientific journey from Einstein’s claim that stars could not collapse to the acceptance of the reality of black holes to a collision of theories over how these weird features exist and function.

The second lecture will bring us up to date with the latest thinking on black holes, and will ask us to change the way we think of them.

Transcript of audience Q and A after the first lecture

SUE LAWLEY: Thank you. Thank you very much indeed, Stephen. Well now we asked listeners what they’d like to ask you and their questions came flooding in, hundreds of them. We’ve chosen a representative selection of topics and invited some of those listeners to come and put their questions in person. You’ll appreciate, audience, that we had to give Stephen the questions beforehand, so that he could programme his answers into his computer. This is done letter by letter through the movement of his facial muscles and you’ll hear little tiny bleeps as the infrared detector picks up those movements. It’s not a speedy process, round about a word a minute, but the answers are all in there now. So if you’re ready, Professor, let me begin by asking Andy Fabian, who’s an astronomer and astrophysicist – he's the Director of the Institute of Astronomy at Cambridge and therefore a colleague of Stephen's – Andy, your question please?

ANDY FABIAN: Stephen, much of the work by yourself and others on issues such as the potential loss of information in black holes and on radiation from black holes is theoretical and lacks observational support so far. Do you see ways to change that situation using the many and varied observations now routinely being made of accreting black holes throughout the cosmos?

SUE LAWLEY: Stephen?

STEPHEN HAWKING: I assume you are referring to the area increase law for black hole horizons. The best way of testing this is black hole collisions rather than accretion.

SUE LAWLEY: Well you got pretty short shrift there, I have to say. (laughter) Perhaps you should tell us what the difference is between accreting black holes and black hole collisions?

ANDY FABIAN: Well black hole collisions are when you have two black holes colliding with each other and merging together. Accretion is just matter dribbling into the black hole steadily and it produces enormous amounts of energy release, very luminous things in the universe.

SUE LAWLEY: Do you foresee that there will be evidential proof of what Stephen is talking about? As you say, it's all theoretical at the moment.

ANDY FABIAN: It would be fantastic to find observational proof of it, but I myself don't see how to do it.

SUE LAWLEY: Okay well let's pursue this theme of what black holes get up to when we're looking at them, and indeed when we're not, and turn to a group of young enthusiasts here from the West Midlands. They're pupils from Barr Beacon Secondary School in Walsall and they're aged around 12 or 13. Kate Harris, you're their teacher. How have you got them interested in cosmology and everything else?

KATE HARRIS: Well I'm their form tutor, so I look after them every morning. I received an email from one of the science teachers who's with us, Dr Butterworth, about Stephen's lecture and told them about it. And they were so keen to know more because firstly they've seen him in 'The Big Bang Theory'… (laughter)

SUE LAWLEY: This is the television … the American sitcom?

KATE HARRIS: Yes. And also they are keen science enthusiasts. They just wanted to know more.

SUE LAWLEY: Yeah, so endlessly interested. Well let's have a question from one of them. Aruniya Muraleedaran, you're aged 12. What's your question?

ARUNYA MURALEEDARAN: What kind of things would happen if one black hole collided with another one?

STEPHEN HAWKING: If two black holes collide and merge to form a single black hole, the area of the event horizon around the resulting black hole is greater than the sum of the areas of the event horizons around the original black holes.

SUE LAWLEY: Did you understand that, Aruniya? Did you get your head round it? (laughter) Well, as I understand it, it's when two black holes collide, the total circumference is greater than the sum of the two parts. The whole area increases. Got it?

ARUNYA MURALEEDARAN: I've got it now. (laughter) What about you? Did you … Do you want to say something?

STUDENT: Yeah, I did understand it. SUE LAWLEY: You did?

STUDENT: A bit, a bit. (laughter)

APPLAUSE

SUE LAWLEY: Well maybe it was because I explained it to you. (laughter) Now to a rather more personal question – and we received many of them actually. This is from a 17 year old Radio 4 listener. His name is Duncan McKinnon. You told us, Duncan, that Stephen had been an inspiration to you. In what way?

DUNCAN McKINNON: Well watching the film with him, it was really inspirational how he managed to carry on with his dreams and goals.

SUE LAWLEY: You mean the film 'The Theory of Everything' … DUNCAN McKINNON: Yeah, yeah.

SUE LAWLEY: … which starred Eddie Redmayne … DUNCAN McKINNON: Yeah.

SUE LAWLEY: … for which he won an Oscar of course. Great film, wasn't it? Okay, like to put your question?

DUNCAN McKINNON: I would like to ask you what inspired you to keep on going despite all the rough times in your life?

SUE LAWLEY: Stephen?

STEPHEN HAWKING: I think my work and a sense of humour have kept me going. When I turned 21 my expectations were reduced to zero. You probably know this already because there's been a movie about it. In this situation, it was important that I came to appreciate what I did have. Although I was unfortunate to get motor neurone disease, I have been very fortunate in almost everything else. I have been lucky to work in theoretical physics at a fascinating time, and it's one of the few areas in which my disability was not a serious handicap. It's also important not to become angry, no matter how difficult life may seem, because you can lose all hope if you can't laugh at yourself and life in general.

SUE LAWLEY: We have here Lucy Hawking, Stephen's daughter, just towards the front there. Lucy, you have seen Stephen over the past four decades if you don't mind my saying that. (laughter)
LUCY HAWKING: That's a little personal, Sue. (laughter)

SUE LAWLEY: I apologise, Lucy.

LUCY HAWKING: That's okay. It's radio, Sue.

STEPHEN HAWKING: (interjecting) I would bring back Einstein. (laughter)

SUE LAWLEY: Interjection from my right. You've seen him, Lucy, weather some pretty rough times. What do you put his resilience and this determination down to?

LUCY HAWKING: I think he's enormously stubborn (laughter) and has a very enviable wish to keep going and the ability to summon all his reserves, all his energy, all his mental focus and press them all into that goal of keeping going. But not just to keep going for the purposes of survival, but to transcend this by producing extraordinary work, writing books, giving lectures, inspiring other people with neurodegenerative and other disabilities, and being a family man, a friend and a colleague to so many … so many people and keeping up with friends across the world. So I think there … there are lots and lots of elements there, but I do think the stubbornness, the will to live and – like he says himself – the sense of humour to laugh at it, at the end of the day is what has …

STEPHEN HAWKING: (interjecting) I would bring back Einstein. (laughter/applause) He would be amazed at how much general relativity has advanced our understanding of the world.

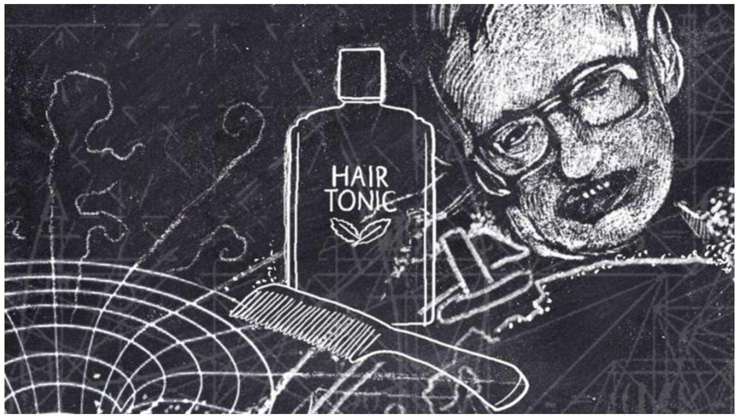
LUCY HAWKING: I think that was his way of asking me to stop talking. (laughter)

SUE LAWLEY: And there we must end. Thank you for making this a memorable event. There's a mass of science on the BBC Reith website, including Robert Oppenheimer, whom Stephen mentioned – one of the fathers of the atom bomb; the astrophysicist Martin Rees; the radio astronomer Bernard Lovell and many more. There's an archive of recordings and transcripts going back to 1948, so do have a look.

For now our thanks to our hosts here at the Royal Institution in London and of course huge thanks to our Reith Lecturer, Professor Stephen Hawking.

THE REITH LECTURES 2015

Reith Lecturer: Professor Stephen Hawking Lecture 1: Do black holes have no hair?



SUE LAWLEY: Hello and welcome to the BBC Reith Lectures. We're at the Royal Institution of Great Britain in the West End of London. It was founded in 1799, to encourage people (and I quote) 'to think more deeply about the wonders and applications of science'. Can there be a better person to fulfil that ambition than this year's lecturer?

When we advertised his name on the airwaves, 20,000 listeners applied for tickets. So I am looking at 400 lucky people gathered here in this historic lecture theatre.

A little bit first about the man who commands such interest: He was a brilliant, though by his own admission 'lazy' physics student at Oxford in the 1960s (the course was 'ridiculously easy' he said). (laughter) But the career which followed, like the stars he loves so much, has shone brightly ever since. Despite being diagnosed with a rare form of Motor Neurone Disease when he was 21 and the physical deprivations it has caused, his work on the laws which govern the universe have been ground-breaking.

The subject of his Reith Lectures is – what else – Black Holes. They've held a fascination for him for the past half century. Virtually invisible and billions of miles away, we nevertheless regard them as menacing. A mistake, says our lecturer – if we could understand them, then we could possibly unlock the secrets of the Universe.

Ladies and Gentlemen, please welcome the world's most famous scientist and the BBC Reith Lecturer, Professor Stephen Hawking.

APPLAUSE

Stephen, welcome. The last time we broadcast together, it was Christmas 1992 and it was on another BBC radio programme, and you were struggling to choose between chocolate mousse and crème brulee. Yeah – it was Desert Island Discs and that was to be your luxury. I wonder if you remember this? Your mother has said that you always had what she described as a strong sense of wonder. "I could see that the stars could draw him", she said. Do you remember that?

STEPHEN HAWKING: I remember coming home late one night from London. In those days they turned the street lights out at midnight to save money. I saw the night sky as I had never seen it before, with the Milky Way going right across. There won't be street lights on my desert island, so I should get a good view of the stars.

SUE LAWLEY: Well, that was 23 years ago and you didn’t really fancy being castaway, I recall:

STEPHEN HAWKING: Can you hear me?

SUE LAWLEY: We can.

STEPHEN HAWKING: 23 years ago, the idea of being stuck on a desert island filled me with horror. At that time, I wanted to be in the heart of the action, where things were happening, not stuck in some remote quiet spot. Now that I am older, a desert island suddenly sounds quite appealing. (laughter) I might get much more work done. But I still don't want to go if there's no crème brulee. (laughter) Physics is fascinating but after all, you can't have it for pudding.

SUE LAWLEY: Well right now – physics is the main course. So serve it up if you would, Stephen. Ladies and Gentlemen – Lecture Number One is entitled Do Black Holes Have no Hair?

STEPHEN HAWKING: My talk is on black holes. It is said that fact is sometimes stranger than fiction, and nowhere is that more true than in the case of black holes. Black holes are stranger than anything dreamed up by science fiction writers, but they are firmly matters of science fact. The scientific community was slow to realize that massive stars could collapse in on themselves, under their own gravity, and how the object left behind would behave.

Albert Einstein even wrote a paper in 1939, claiming stars could not collapse under gravity, because matter could not be compressed beyond a certain point. Many scientists shared Einstein's gut feeling. The principal exception was the American scientist John Wheeler, who in many ways is the hero of the black hole story. In his work in the 1950s and ‘60s, he emphasized that many stars would eventually collapse, and the problems that posed for theoretical physics. He also foresaw many of the properties of the objects which collapsed stars become, that is, black holes.

During most of the life of a normal star, over many billions of years, it will support itself against its own gravity, by thermal pressure, caused by nuclear processes, which convert hydrogen into helium. Eventually, however, the star will exhaust its nuclear fuel. The star will contract. In some cases, it may be able to support itself as a white dwarf star. However Subrahmanyan Chandrasekhar showed in 1930, that the maximum mass of a white dwarf star, is about 1.4 times that of the Sun. A similar maximum mass was calculated by Soviet physicist, Lev Landau, for a star made entirely of neutrons.

What would be the fate of those countless stars, with greater mass than a white dwarf or neutron star, when they had exhausted nuclear fuel? The problem was investigated by Robert Oppenheimer, of later atom bomb fame. In a couple of papers in 1939, with George Volkoff and Hartland Snyder, he showed that such a star could not be supported by pressure. And that if one neglected pressure, a uniform spherically systematic symmetric star would contract to a single point of infinite density. Such a point is called a singularity. All our theories of space are formulated on the assumption that space-time is smooth and nearly flat, so they break down at the singularity, where the curvature of space-time is infinite. In fact, it marks the end of time itself. That is what Einstein found so objectionable.

Then the war intervened. Most scientists, including Robert Oppenheimer, switched their attention to nuclear physics, and the issue of gravitational collapse was largely forgotten. Interest in the subject revived with the discovery of distant objects, called quasars. The first quasar, 3C273, was discovered in 1963. Many other quasars were soon discovered. They were bright, despite being at great distances. Nuclear processes could not account for their energy output, because they release only a percent fraction of their rest mass as pure energy. The only alternative was gravitational energy, released by gravitational collapse.

Gravitational collapses of stars were re-discovered. It was clear that a uniform spherical star would contract to a point of infinite density, a singularity.

The Einstein equations can't be defined at a singularity. This means at this point of infinite density, one can't predict the future. This implies something strange could happen whenever a star collapsed. We wouldn't be affected by the breakdown of prediction, if the singularities are not naked, that is, they are not shielded from the outside. When John Wheeler introduced the term black hole in 1967, it replaced the earlier name, frozen star. Wheeler's coinage emphasized that the remnants of collapsed stars are of interest in their own right, independently of how they were formed. The new name caught on quickly. It suggested something dark and mysterious, But the French, being French, saw a more risque meaning. (laughter) For years, they resisted the name trou noir, claiming it was obscene. (laughter) But that was a bit like trying to stand against Le Week-end, and other Franglais. In the end, they had to give in. Who can resist a name that is such a winner?

From the outside, you can't tell what is inside a black hole. You can throw television sets, diamond rings, or even your worst enemies into a black hole, and all the black hole will remember is the total mass, and the state of rotation. John Wheeler is known for expressing this principle as “a black hole has no hair”. To the French, this just confirmed their suspicions. (laughter)

A black hole has a boundary, called the event horizon. It is where gravity is just strong enough to drag light back, and prevent it escaping. Because nothing can travel faster than light, everything else will get dragged back also. Falling through the event horizon is a bit like going over Niagara Falls in a canoe. If you are above the falls, you can get away if you paddle fast enough, but once you are over the edge, you are lost. There's no way back. As you get nearer the falls, the current gets faster. This means it pulls harder on the front of the canoe than the back. There's a danger that the canoe will be pulled apart. It is the same with black holes. If you fall towards a black hole feet first, gravity will pull harder on your feet than your head, because they are nearer the black hole. The result is you will be stretched out longwise, and squashed in sideways. If the black hole has a mass of a few times our sun you would be torn apart, and made into spaghetti before you reached the horizon. However, if you fell into a much larger black hole, with a mass of a million times the sun, you would reach the horizon without difficulty. So, if you want to explore the inside of a black hole, make sure you choose a big one. (laughter) There is a black hole with a mass of about four million times that of the sun, at the centre of our Milky Way galaxy.

Although you wouldn't notice anything particular as you fell into a black hole, someone watching you from a distance would never see you cross the event horizon. Instead, you would appear to slow down, and hover just outside. Your image would get dimmer and dimmer, and redder and redder, until you were effectively lost from sight. As far as the outside world is concerned, you would be lost forever.

There was a dramatic advance in our understanding of these mysterious phenomena with a mathematical discovery in 1970. This was that the surface area of the event horizon, the boundary of a black hole, has the property that it always increases when additional matter or radiation falls into the black hole. These properties suggest that there is a resemblance between the area of the event horizon of a black hole, and conventional Newtonian physics, specifically the concept of entropy in thermodynamics. Entropy can be regarded as a measure of the disorder of a system, or equivalently, as a lack of knowledge of its precise state. The famous second law of thermodynamics says that entropy always increases with time. This discovery was the first hint of this crucial connection.

Although there is clearly a similarity between entropy and the area of the event horizon, it was not obvious to us how the area could be identified as the entropy of a black hole itself. What would be meant by the entropy of a black hole? The crucial suggestion was made in 1972 by Jacob Bekenstein, who was a graduate student at Princeton University, and then at the Hebrew University of Jerusalem. It goes like this. When a black hole is created by gravitational collapse, it rapidly settles down to a stationary state, which is characterized by only three parameters: the mass, the angular momentum, and the electric charge. Apart from these three properties, the black hole preserves no other details of the object that collapsed.

His theorem has implications for information, in the cosmologist's sense of information: the idea that every particle and every force in the universe has an implicit answer to a yes-no question. The theorem implies that a large amount of information is lost in a gravitational collapse. For example, the final black-hole state is independent of whether the body that collapsed was composed of matter or antimatter, or whether it was spherical or highly irregular in shape. In other words, a black hole of a given mass, angular momentum and electric charge, could have been formed by the collapse of any one of a large number of different configurations of matter. So what appears to be the same black hole could be formed by the collapse of a large number of different types of star. Indeed, if quantum effects are neglected, the number of configurations would be infinite, since the black hole could have been formed by the collapse of a cloud of an indefinitely large number of particles, of indefinitely low mass. But could the number of configurations really be infinite?

The uncertainty principle of quantum mechanics implies that only particles with a wavelength smaller than that of the black hole itself, could form a black hole. That means the wavelength would be limited: it could not be infinite. It therefore appears that the number of configurations that could form a black hole of a given mass, angular momentum and electric charge, although very large, may also be finite. Jacob Bekenstein suggested that from this finite number, one could interpret the entropy of a black hole. This would be a measure of the amount of information that was irretrievably lost during the collapse when a black hole was created.

The apparently fatal flaw in Bekenstein's suggestion was that if a black hole has a finite entropy that is proportional to the area of its event horizon, it also ought to have a finite temperature, which would be proportional to its surface gravity. This would imply that a black hole could be in equilibrium with thermal radiation, at some temperature other than zero. Yet according to classical concepts, no such equilibrium is possible, since the black hole would absorb any thermal radiation that fell on it, but by definition would not be able to emit anything in return. It cannot emit anything. It cannot emit heat.

This is a paradox. And it's one which I am going to return to in my next lecture, when I'll be exploring how black holes challenge the most basic principle about the predictability of the universe, and the certainty of history, and asking what would happen if you ever got sucked into one. Thank you.

APPLAUSE

SUE LAWLEY: Thank you. Thank you very much indeed, Stephen. Well now we asked listeners what they'd like to ask you and their questions came flooding in, hundreds of them. We've chosen a representative selection of topics and invited some of those listeners to come and put their questions in person. You'll appreciate, audience, that we had to give Stephen the questions beforehand, so that he could programme his answers into his computer. This is done letter by letter through the movement of his facial muscles and you'll hear little tiny bleeps as the infrared detector picks up those movements. It's not a speedy process, round about a word a minute, but the answers are all in there now. So if you're ready, Professor, let me begin by asking Andy Fabian, who's an astronomer and astrophysicist – he's the Director of the Institute of Astronomy at Cambridge and therefore a colleague of Stephen's – Andy, your question please?

ANDY FABIAN: Stephen, much of the work by yourself and others on issues such as the potential loss of information in black holes and on radiation from black holes is theoretical and lacks observational support so far. Do you see ways to change that situation using the many and varied observations now routinely being made of accreting black holes throughout the cosmos?

SUE LAWLEY: Stephen?

STEPHEN HAWKING: I assume you are referring to the area increase law for black hole horizons. The best way of testing this is black hole collisions rather than accretion.

SUE LAWLEY: Well you got pretty short shrift there, I have to say. (laughter) Perhaps you should tell us what the difference is between accreting black holes and black hole collisions?

ANDY FABIAN: Well black hole collisions are when you have two black holes colliding with each other and merging together. Accretion is just matter dribbling into the black hole steadily and it produces enormous amounts of energy release, very luminous things in the universe.

SUE LAWLEY: Do you foresee that there will be evidential proof of what Stephen is talking about? As you say, it's all theoretical at the moment.

ANDY FABIAN: It would be fantastic to find observational proof of it, but I myself don't see how to do it.

SUE LAWLEY: Okay well let's pursue this theme of what black holes get up to when we're looking at them, and indeed when we're not, and turn to a group of young enthusiasts here from the West Midlands. They're pupils from Barr Beacon Secondary School in Walsall and they're aged around 12 or 13. Kate Harris, you're their teacher. How have you got them interested in cosmology and everything else?

KATE HARRIS: Well I'm their form tutor, so I look after them every morning. I received an email from one of the science teachers who's with us, Dr Butterworth, about Stephen's lecture and told them about it. And they were so keen to know more because firstly they've seen him in 'The Big Bang Theory'… (laughter)

SUE LAWLEY: This is the television … the American sitcom?

KATE HARRIS: Yes. And also they are keen science enthusiasts. They just wanted to know more.

SUE LAWLEY: Yeah, so endlessly interested. Well let's have a question from one of them. Aruniya Muraleedaran, you're aged 12. What's your question?

ARUNIYA MURALEEDARAN: What kind of things would happen if one black hole collided with another one?

STEPHEN HAWKING: If two black holes collide and merge to form a single black hole, the area of the event horizon around the resulting black hole is greater than the sum of the areas of the event horizons around the original black holes.

SUE LAWLEY: Did you understand that, Aruniya? Did you get your head round it? (laughter) Well, as I understand it, it's when two black holes collide, the total circumference is greater than the sum of the two parts. The whole area increases. Got it?

ARUNIYA MURALEEDARAN: I've got it now. (laughter) What about you? Did you … Do you want to say something?

STUDENT: Yeah, I did understand it.

SUE LAWLEY: You did?

STUDENT: A bit, a bit. (laughter)

APPLAUSE

SUE LAWLEY: Well maybe it was because I explained it to you. (laughter) Now to a rather more personal question – and we received many of them actually. This is from a 17 year old Radio 4 listener. His name is Duncan McKinnon. You told us, Duncan, that Stephen had been an inspiration to you. In what way?

DUNCAN McKINNON: Well watching the film with him, it was really inspirational how he managed to carry on with his dreams and goals.

SUE LAWLEY: You mean the film 'The Theory of Everything' …

DUNCAN McKINNON: Yeah, yeah.

SUE LAWLEY: … which starred Eddie Redmayne …

DUNCAN McKINNON: Yeah.

SUE LAWLEY: … for which he won an Oscar of course. Great film, wasn't it? Okay, like to put your question?

DUNCAN McKINNON: I would like to ask you what inspired you to keep on going despite all the rough times in your life?

SUE LAWLEY: Stephen?

STEPHEN HAWKING: I think my work and a sense of humour have kept me going. When I turned 21 my expectations were reduced to zero. You probably know this already because there's been a movie about it. In this situation, it was important that I came to appreciate what I did have. Although I was unfortunate to get motor neurone disease, I have been very fortunate in almost everything else. I have been lucky to work in theoretical physics at a fascinating time, and it's one of the few areas in which my disability was not a serious handicap. It's also important not to become angry, no matter how difficult life may seem, because you can lose all hope if you can't laugh at yourself and life in general.

SUE LAWLEY: We have here Lucy Hawking, Stephen's daughter, just towards the front there. Lucy, you have seen Stephen over the past four decades if you don't mind my saying that. (laughter)

LUCY HAWKING: That's a little personal, Sue. (laughter)

SUE LAWLEY: I apologise, Lucy.

LUCY HAWKING: That's okay. It's radio, Sue.

STEPHEN HAWKING: (interjecting) I would bring back Einstein. (laughter)

SUE LAWLEY: Interjection from my right. You've seen him, Lucy, weather some pretty rough times. What do you put his resilience and this determination down to?

LUCY HAWKING: I think he's enormously stubborn (laughter) and has a very enviable wish to keep going and the ability to summon all his reserves, all his energy, all his mental focus and press them all into that goal of keeping going. But not just to keep going for the purposes of survival, but to transcend this by producing extraordinary work, writing books, giving lectures, inspiring other people with neurodegenerative and other disabilities, and being a family man, a friend and a colleague to so many … so many people and keeping up with friends across the world. So I think there … there are lots and lots of elements there, but I do think the stubbornness, the will to live and – like he says himself – the sense of humour to laugh at it, at the end of the day is what has …

STEPHEN HAWKING: (interjecting) I would bring back Einstein. (laughter/applause) He would be amazed at how much general relativity has advanced our understanding of the world.

LUCY HAWKING: I think that was his way of asking me to stop talking. (laughter)

SUE LAWLEY: And there we must end. Thank you for making this a memorable event. There's a mass of science on the BBC Reith website, including Robert Oppenheimer, whom Stephen mentioned – one of the fathers of the atom bomb; the astrophysicist Martin Rees; the radio astronomer Bernard Lovell and many more. There's an archive of recordings and transcripts going back to 1948, so do have a look.

For now our thanks to our hosts here at the Royal Institution in London and of course huge thanks to our Reith Lecturer, Professor Stephen Hawking.