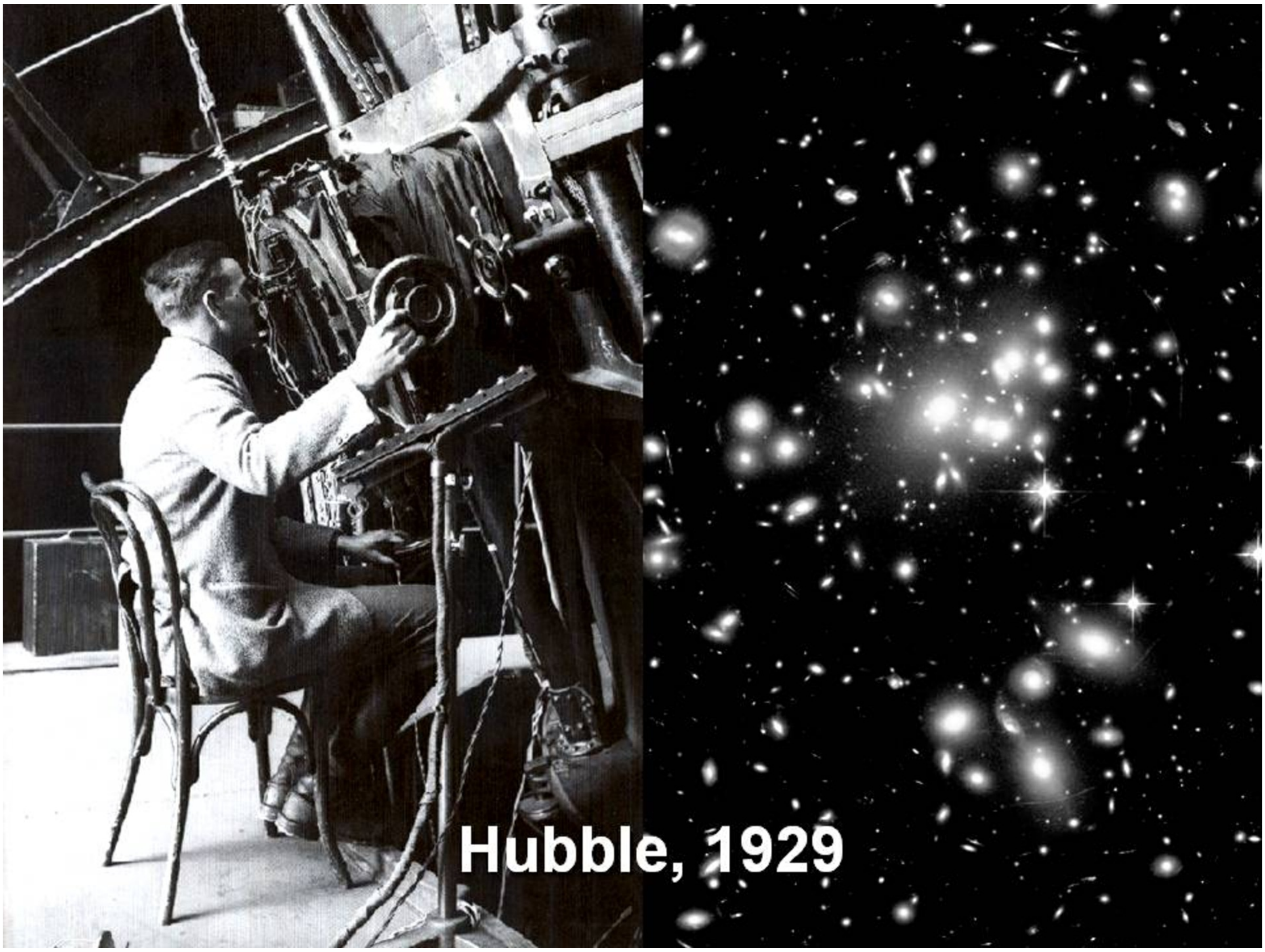
The End of Space and Time?
Transcript

Date: Tuesday, 20 March 2012 - 3:00PM

Location: Barnard's Inn Hall



20 March 2012

The End Of Space And Time?

Professor Robbert Dijkgraaf

Thank you so much, Michael, for this very kind introduction and for the wonderful opportunity to speak here in an institution that has such a long history in the public outreach of the sciences, I think something that we cannot do enough.

Today, I will tell you a grand story, which is our thinking of space and time, and in some sense, what is the role of geometry, mathematics in understanding the universe. This goes back certainly to the beginning of modern science. There is this wonderful image of Galileo, of the book of “Nature”, that is being read, but before to read it, you have to know the language in which it is written, and for Galileo, this was the language of Euclidian mathematics – triangles, circles and other geometrical figures. I think this is a long tradition.

If you go back in more recent history, for instance, Richard Feynman, the famous particle physicist, he has said that if you really do not know mathematics – and do not be worried, there will not be many equations today – but if you do not really know mathematics, you cannot get across the real feeling of the beauty of nature. Now, Feynman is also famous for having said that “If all mathematics disappeared today, physics would be set back exactly one week!” I always thought that was a very clever remark, until a famous mathematician gave the right response to this and said, “Well, this was the week that God created the world!” So I say two to one mathematics to physics!

The amazing thing is that the mathematics that we are talking about today is, in some sense, very far away from our everyday intuition. We talk about the very large-scale structures in the universe, the theory of relativity, and the very small-scale structures, the quantum theory. I think we live in an amazing time, where these two concepts are actually coming together. It is really the snake biting its own tail, and it is actually happening right in that time that we are now, in the history of science.

If you see space and time, which I will proclaim to be near to their end, they have quite an evolution of themselves. Space started among the Greeks as something infinitely rigid, almost like a big stage on which the natural phenomena would play their part. Time, according to Newton, was this big clock that would tick and set the stage directions.

Now, this image of directed play really changed, very much, 100 years ago when Einstein came, and he famously said that, “Time is the fourth dimension.” It is very difficult to visualise four dimensions, but let me just help you to get across this image of this extra dimension. The best way to do this is think of a movie: so if you think of this movie, it has got two-dimensions, and think of the individual pictures that make up the movie reel, and now put these pictures on top of each other so that you basically get a stack of pictures. If you follow that, you will see that a single particle will actually become aligned in the so-called space-time. That is what Einstein said: mysteriously, all of this formed one continuum, which is pictured here on the right hand side, and everything that moves, or not move, will have these spaghetti strands that you see here on the right hand side. So we all are now moving in this space-time continuum, and Einstein said that this is the object that we want to study, so anything you have to say about space, you are also saying about time.

This went on. Not only did we have this unification of space and time but the next ingredient was that space, the stage, so to say, is not rigid, it is flexible, it can curve, it can shape, and it does so under the influence of energy and mass, and that is the phenomena that we call gravitation. So, anything that carries mass or energy will curve the space and time around and thereby space and time became no longer the stage, but an active player in the game. Space and time are something which has physical properties and a future in physical laws, and in fact, it is the influence of this curvature that describes the motion of particles under the influence of gravity. This was the grand scheme that Einstein had, that all of physics, in his persuasion, was geometry, and I think his claim, his intent in life, particularly in the latter part of his life, was to put everything in this geometrical form. Also, the theory of elementary particles, which in some sense was a very fruitless effort, and one of my conclusions today, this is also not the line of argument that you want to follow because, in some sense, quantum theory will probably be victorious over the underlying ideas of geometry that were so dear to Einstein and all of us.

Of course, Einstein was the first one that was able to do a computation that nobody did before, again in the history of science, namely, compute what happens to the universe. He could put the universe in his equations, and he saw that the universe was expanding, and he could also conclude that, therefore, in the past, it would have been contracting and getting an inconsistent conclusion – namely, there should be a moment where space and time started. When he discovered this, he said that this is a bad thing; the only thing that I now have to do is to change my theory. So, famously, he took his equations, which roughly, in words, say that that expansion of the universe is driven by the matter and energy and the curvature of space and time, and he added a correction to it, which he called the cosmological constant, with the Greek letter Lambda, to just stop the expansion of the universe.

Well, later, he called this intervention his biggest blunder because this was something that, at that time, he could have made a wonderful prediction – namely, “I predict that the universe is expanding and please, astronomers, look and see this phenomenon.” He did not. But with Einstein, anything he did was brilliant, so even his biggest blunder was brilliant.

Of course, ten years later, roughly, the astronomers in particular had all seen that the galaxies that we see in the sky are expanding, the universe expanding, and the first proof of the so-called Big Bang theory finally comes in the 1960s when two engineers, with a microwave telescope or receiver, Penzias and Wilson, discovered the first light emitted at the Big Bang – that is the famous cosmic microwave background radiation. I never really did the calculation myself, but apparently, if you take your television set and disconnect it and you see this static on your screen, then one in 100 of these pixels is actually turned white because of a cosmic background radiation, so actually it is the cosmos influencing with your television reception, and it is amazing that these are photons, particles that travelled for 13.7 billion years to hit your television screen, which is of course a very special effect.

Well, now, I think the evolving universe, the Big Bang, is part of our culture, and in fact, these images and the discoveries that are made are getting more and more exact and precise. We are living in the age of precision cosmology, and for instance, satellites, like the WMAP Satellite take very beautiful pictures which are celestial globes, as they made in the sixteenth and seventeenth century, where you had the zodiac, but now, it shows the very early universe, the first light that was emitted by the universe when, 400,000 years after the Big Bang, it became transparent. The small fluctuations led to everything you see around, just like a pointillist painting.

The first small variations of energy distribution come together and they form, at the beginning, very violent galaxies, and then these galaxies form and a lot of stars, modern forms of stars, and finally this structure in the universe develops a very particular nature, the strands going through space, and now we are in the beautiful position that we can reconstruct these 13.7 billion years of history. We have a very precise – in the order of 0.01 percent of the description of this particular cosmological evolution.

Of course, this is wonderful, this statement that shows the power, in some sense, of a lot of Einstein’s ideas, and now, 100 years later, we are in the position to make experimental verifications of all the initial concepts that he introduced. However, there are still lots of questions. For instance, there is this question of why is the universe so flat? Why is it so large and full of structure? And also, here, we have some good ideas why this is actually the case, and this has to do with the fact that, before, at the very, very beginning of the Big Bang, just after there was a period when the universe was also expanding but it was at actually a violent rate. This is the inflation, cosmological inflation, which is something very different from the economic inflation, in the sense that it adds roughly 26 zeros to the size of the universe in a very brief period. So, we believe that the universe, in the very, very, very beginning, and we are talking about really fractions of a second, expanded gigantically and produced this random pattern that we now can follow very beautifully through the equations of cosmology to see how it shaped our universe.

The amazing thing of this picture is that, in some sense, it is a gigantic microscope. It takes the world of the universe as a magnification of a very small patch of something that was there before, and this thing that is there before, this randomness, is something that really belongs to the theory of quantum mechanics. So we feel that, in order to understand the very beginning of the universe, we have to understand the laws of the very small elementary particles quantum theory to describe the structures that we find there.

To find any kind of solution to the grand picture of the universe, we have to study the very small, which is known to us as the quantum world. Now, in the quantum world, it was not obvious, for a long time, that the intuition that physicists have had for many, many centuries, that namely mathematics is the appropriate question to understand the structure, actually is working.

In fact, if you see pictures that are coming out of particle accelerators, they look like a big mess, so is there any kind of beauty? Is there mathematics behind this? In fact, if you go to, for instance, the 1960s, there was a period where people were actually arguing that there is no such thing – the elementary particle physics is like a black box, something you cannot open, something comes in, something comes out and you can study the correlation between the two. At that time, it was, of course, the hippy period – people were thinking kind of from a holistic point of view, and declared in principle that this black box could not be opened.

This was, historically speaking, the famous last words, because not only could this box be opened, it turned out, inside it was in fact quite a small formula. This is my way of writing the so-called formula for the standard model, which is the description of the fundamental laws of particle physics:

$$L = F^2 + \psi\left(i\not{D} + \varphi\right)\psi + \left|D\varphi\right|^2 + \left(\left|\varphi\right|^2 - 1\right)$$

You know, this is all written in formula lines that you could give a lecture to a mathematician who would know a single thing of mathematics but would understand that these are natural geometrical objects. So, again, it is geometry that is, in a very deep way, responsible for it.

The standard model of particle physics is something that fits on the t-shirt. It is a handful of particles and it is a very natural way in which they interact. I think it is one of the great triumphs of modern physics that in fact this single equation or this t-shirt is able to describe all the physics that we see around us here, all the matter, all the forces, all the radiation.

And, if you look at this distribution of particles, there are two feelings that a physicist had: one is absolutely beauty and elegance, amazing that the world works like this; and the second feeling is what was expressed by the Nobel Prize winning physicist I. I. Rabi when one of these particles was discovered: “Who ordered this?” So you look at this and you say, “Why quarks?” Why this funny phenomena that anything in nature seems to come in three families, small, medium, large, and why are there three colours of quarks? There are lots of questions, questions that typically your child would ask, and of course, these are good questions in the sense they are questions that basically do not have an answer. Physics is at a loss and they try to figure out whether this fits in a grand pattern. So, if you start to rearrange the pieces of the puzzle, then, for instance, you can see that you can rearrange them in more symmetric patterns which seem to suggest that this is just part of a bigger story, there are bigger symmetries here that we cannot see in nature but that perhaps are behind the physical phenomena that we see.

Nature has given us a few clues that suggest this is not the end of the story, and perhaps the most famous one is again coming from cosmology – you must have heard about this – the existence of dark matter. If you look at the way in which gravity is acting on the stars in a galaxy, then astronomers have discovered that, in order to count it in terms of matter, there is a huge cloud of matter which is dark, invisible and not made out of the particles that we know, surrounding each galaxy, and by indirect measurements, you can actually determine the structure of this dark matter distribution – roughly six times more of that dark matter than there is original matter. Cosmologists look at the structure of the universe and see that these galaxies are not uniformly distributed in the universe. They are clumped together in a large scale structure, these kind of strands that fly basically through space, and by studying the dynamics of matter and dark matter, actually get a very clear model that seemed to fit very well the observed structure of the universe. So we know there are lots and lots of more matter around that we cannot encode at this moment in our physical models.

In the last couple of years, there has been a great survey of cosmological phenomena, particularly also of supernovae, which are stars exploding in galaxies. The moment that a supernova explodes is roughly as bright as a whole galaxy. There are large surveys and by looking at these supernovae, they are kind of little bombs, well, “little” – they are enormous bombs that go off with a fixed amount of energy that gets released. So, by knowing where the supernova is, and you know how much light it would produce, you can get a very good measurement of distances in the universe. The great conclusion of this is that the universe is not only expanding, it is expanding in an accelerating way, so it is only getting faster and faster, and there is a force that actually is pushing the universe apart. This force, which cosmologists call dark energy, is exactly this parameter that Einstein introduced, the so-called biggest blunder, the extra physical phenomena that he conjectured to hold back the universe. In fact, it is there, but it is working just the opposite way that Einstein figured. It is not slowing down the expansion, it is actually adding to the expansion, and in fact, this has dramatic consequences in the sense that, in the end, the universe will be expanding so fast that most of the galaxies that we see now will actually be far, far away and we will actually, in some sense, look into a dark void.

This was a result that got a lot of attention. Last year’s Nobel Prize was in fact awarded to this phenomena. Physicists are in this wonderful position that they know exactly what they do not know! So, 96%, according to these computations, of the universe is either in the form of the dark matter or dark energy, which is just a fancy way of saying there is some physical phenomena that we do not understand but we see its presence, and only 4% of the universe consists of the particles that we describe in our textbooks and that we teach in our lectures about.

I often ask people in other fields, “What is your percentage of dark matter – how much do you know that you do not know?” It would be very interesting to ask this question in economics!

There are also the so-called unknown unknowns, which are things that you do not even know that you do not know them. For instance, this dark energy was in that category ten years ago, because every cosmologist at that time would have claimed that this 4% was everything. So only now we come and discover a very modest position that we only have to find this other 96%. So I always feel that cosmologists and physicists are a little bit like these old people making maps who charted some part of their territory. Of course, there was a large part that was unknown, and it is very difficult to leave that empty, so they sketched all these sea monsters there. So, dark energy and dark matter are represented by the sea monsters, I think, of present day physics, and perhaps the physicists are in this little boat trying to figure out whether these monsters are really there, but we are still mapping it out.

What could be the possible explanation of these effects? These big question marks that are in the sky, and to answer that I want to go back to a completely different question that perhaps some of you have asked once. So, if you learn about elementary particles or molecules, you are told what the property, for instance, of an electron is. So how come that every electron has exactly the same properties? If there is a machine making this, a sort of factory, then actually it is a perfect factory - it makes these individual particles exactly the same.

Now, there is a good answer to this, and this answer was actually given by John Wheeler in a telephone conversation to his then graduate student, Richard Feynman, and Feynman describes this in his Nobel lecture. Feynman would win the Nobel Prize because of this idea. Wheeler calls him up in the middle of the night and asks him this question, "I know the answer, because there is only one electron in whole the universe." Now, I always feel that if your thesis advisor is calling you in the middle of the night, you have to be wondering what he is drinking, but actually, this is typically Wheeler. This is a crazy idea that is crazy enough to be true.

Wheeler was saying suppose this particle not could only go up in time, like we are now doing, but could also go *back*in time. If I could go back in time, I could re-enter this room, stand next to myself, and would be an exact copy of myself, exact really to the last digit, and I could do it another time. So Wheeler was saying suppose this particle could go up and down in space and time and basically make a big knot, what would it signify?

Well, if you think of this as a stack of pictures, on the bottom, you would have a single particle, but in the middle, you would have many, many particles going up and going down, which have exactly the same property because basically it is the same particle. So I think it is a very clever idea.

Feynman immediately said, "Well, then you would have as many particles as anti-particles,"

But now these pictures are known as Feynman Diagrams, so Feynman really took full advantage of this so-called space-time picture of particles, which is how he described it.

In fact, reality is even stranger. For instance, a particle can do the following thing: according to these rules, it can split in two-particles, for a very brief time, and then these two particles are combining again to another particle. These intermediate particles are called virtual particles - you can only see them indirectly. Basically, there is a rule of quantum mechanics that anything is allowed as long as you do it fast enough before it can detect it. I always feel this is something very typical to the Dutch mentality because our whole society is based on this description there, our so-called tolerance. And in fact they are measured in particle accelerators, and there is the ultimate result of this, which is that, for a brief moment of time, two particles can appear out of nothing, of course violating every rule in the book, and then they combine again. Or, if you wish, and you want to think like Wheeler, it is a single particle that goes up in time and down in time and keeps on going round and round and round.

This is not some kind of science fiction phenomenon. This is something that is happening right now and can be measured in a laboratory. In fact, the Dutch physicist, Casimir, after which this effect is named, measured this between two electric plates, in a slightly different context.

Empty space, according to quantum theory – this is my own kind of visualisation of empty space… It is this boiling pot of particles and anti-particles appearing and disappearing. So, space-time is not only curves and shapes, it is also full of life so to say. It has really a physical material that you can study, and if you take a chunk of this quantum space-time, because of all this phenomena, there is energy in it, and this energy, according to quantum theory, that is this dark energy – that is the phenomenon that cosmologists measure. So I like to joke that empty space, the vacuum, is the most fascinating thing to study in physics, but of course writing big grant proposals to study nothing might actually not come across very clear, but in fact, it is what we are doing. The big mysteries really, so to say the old-fashioned ether, studying nothing, studying space and time itself, and as we see, it is really the place where these two theories come together, so what we are studying is a thing called quantum gravity: how does space and time behave in the quantum world? And we know there is such a thing because, if you look at the various forces of nature, the three forces that are there in the standard model, and you compare them to gravity, you see that when the energy scale goes up and up and up, that gravity gets the same strength as the other forces. So there should be a moment, even before this very brief split of a second in which inflation starts, where space-time itself becomes a quantum phenomenon, so not only are the particles themselves allowed to do anything they want, space-time itself is allowed to do this, and therefore it stops.

Max Planck, the father of quantum mechanics, in his first paper ever written on quantum theory, immediately realised this. He realised that if quantum mechanics were there, then the ultimate consequence would be that there is a smaller size, in physics, a smaller size to space and time. It is a little bit like if you take a computer screen and zoom in and zoom in, you see, at some point, you get to see these pixels, and what physics is telling us is that space itself should have this property. If you put it on a gigantic microscope, there is no longer space, there are little bits, and there are pixels. There are quantum bits roughly the size of this Planck length.

This Planck length is incredibly small. If you look at the various scales in physics, there is the smaller scale which is the Planck scale, there is a larger scale which is the size of the visible universe, the Hubble scale, and if you go from left to right, from the smallest to the largest structure imaginable, there are 60 steps of a factor of ten. One way to visualise this is right, very convenient, in the middle, the geometrical mean of the two is the scale - it's roughly ten micron – it is the scale of a human cell. So if you want to think of how small the Planck scale is, take the whole universe, make a scale model of it as small as a bacterium, and now think of a bacterium inside the scale model of the universe. It is incredible, but of course the most incredible thing is that this stops. There is a larger scale and there is a smaller scale. That means that, in some sense, putting this under the microscope will not help anymore – there is no way in which we could get to smaller structure.

Where do we see these phenomena? Is this relevant physics? I think the amazing thing is that there is a laboratory where you can test these ideas, and it is again a cosmological laboratory, and it is black holes. So black holes are something that were in science fiction books twenty years ago, but now are part of the standard description of our universe. For instance, there are black holes inside every galaxy we see, often millions and millions of suns, with the weight, mass, of millions and millions of suns. They are extremely violent. For instance, if zoom in to the centre of our own galaxy, you see that the nearby stars are moving around quite violently and fast, at speeds which are percentages of the speed of light, all surrounding this intergalactic black hole.

For a theoretical physicist like myself, I would draw the so-called space-time picture and then a black hole is something very particular. It is a star that is imploding, its own gravitational force is pulling everything together in the so-called singularity, where the gravitational force becomes incredibly strong, and then, remarkably, this very violent area of the universe is protected by a horizon. There is an area around the black hole, a sphere if you would draw it in three-dimensions, which has a property that, once you are inside, you are doomed, but once you stay outside, you are fine. The reason that you are doomed inside the horizon has to do with a crazy phenomenon that I had time flowing upward. Inside a black hole, time is flowing inward, that is, it is a spatial direction – it is flowing from the boundary of the horizon towards the centre of the black hole. So if you were inside, you would typically say there is a one-metre distance to the centre, in a black hole, you would say there is a three-minute distance to the centre. That is to say you are watching a movie and you know you have only three minutes to go, so you will know it will end when you hit the singularity.

There is a famous set of laws that black holes obey that are very famous in some sense and are very familiar from a standard physics' perspective. The first law is the 2nd Law of Black Hole Thermodynamics, that if you have two of these black holes and they merge together, the area of their horizons, of the new black hole, is larger than the sum of the two original ones. This is something that we know, in some sense, from standard thermal physics, where we call this the 2nd Law of Thermodynamics, which is the phenomenon that entropy always increases.

So, black hole physicists, Bekenstein and Hawking and others, introduced a notion of geometrical entropy, which is a gravitational version that is equal to the area of the horizon. And then there was the famous discovery of Hawking that, if you introduce an entropy, perhaps you can also introduce a temperature, and indeed, he discovered something quite phenomenal: that if you have these laws of quantum mechanics that say that particles can be created out of nothing, for a very brief time. If the same phenomenon happens in the neighbourhood of a black hole, you could have two particles just at the edge of the horizon, one particle being inside and the other particle being outside. The particle inside is basically doomed and will be pulled by the gravitational force to the singularity, while the other particle is now liberated and can escape to infinity. So one of the places where quantum mechanics and relativity interact in a very strong way is in the neighbourhood of a black hole, where it leads to spontaneous radiation out of the black hole – this is called Hawking radiation, and an amazing thing, if you do the computation, you find that the temperature of this thermal radiation in fact is given by the surface gravity of the black hole. Not only do we have entropy but also we have energy, we have temperature and it looks like there is something like thermodynamics going on in black hole physics.

In fact, if you look at a very tiny black hole, you might say, well, it could form by matter colliding, it would live for some time, and then it would radiate out particles, by this Hawking process. So if you look at a very small black hole, it would almost be like a small particle. Particles, as they are formed in our usual accelerators, two particles collide, they make a new particle, could be something like a radioactive particle, so it will decay, and after some time, it will disappear. So it means that if you want to make a little black hole at a certain spot, and put a lot of energy in a certain space, then at some point, that black hole will evaporate, so there will actually be some kind of uncertainty into the time during which this particle will live. This already tells you that space and time are interacting in a very strange way with black hole physics.

In fact, this led to a line of reasoning which I am actually talking about and which goes back to John Wheeler, who was very good on slogans, and he called this phenomena "It from bit". What is "it"? "It" is the universe. And what is "bit"? "Bit" is the entropy that is there. Entropy is information. So he had this image that, if you think of the horizon of a black hole, there is information inside the black hole, and you can compute the amount of information and you find actually that amount of information, it is as if you filled the black hole with zeros and ones, with little bits of information, but you use one bit per square Planck length. So think of this horizon of the black hole as this pixel of the picture of Max Planck that I had, and you can see how much information can you store in a black hole – well, basically, by putting one bit of information of every kind of square Planck length that you can subdivide, in which you can subdivide the horizon of the black hole.

So this leads to what physicists now call the Holographic Principle. Perhaps the physics of the black hole and anything outside it at least can be encoded by putting this information on the surface of this horizon, which, in some sense, is the edge of space. We have already argued that inside the black hole, space and time come to an end, but it does not really end, but basically this theory says just cut it off, create a screen, which is the thing that surrounds the black hole, forget anything inside, and project all of physics in terms of the information on that black hole horizon, the zeros and ones that are sitting there. It is a rather radical idea because it tells you that there is information in the underlying layer of understanding all of quantum geometrical physics.

Can this idea be tested? It can be tested in a theoretical way, and one way is in string theory. I am not giving a course on string theory here, but of course, you must have heard of string theory, something where the notion of an elementary particle is generalised to a one-dimensional object, a little bit of string. But one thing that has happened within the last ten years is that a lot of research has been devoted to studying how does string theory encode for black holes. String theory is supposedly a theory of quantum gravity, combining gravity and quantum physics in a unique way. So what does it tell us about black holes?

Within the horizon of the black hole, you have gravitation, and gravitation is described, in string theory, in terms of these so called closed strings, these little loops of elementary loops, that are running around and forming the shape of space and time, the curvature of space. So we can replace these closed strings by Einstein's description of space-time.

What happens to these strings when they are very close to the black hole? What happens is that these strings halfway fall through, so there is half of a string sticking out, almost like somebody in the sea waving his hands, you know, "Help!" So there are these open strings that are attached to the horizon, to the surface of the black hole, so they are tethered to the two endpoints that are fixed on the horizon and you can describe this system. In fact, the mathematical description of this, of this neighbourhood of the horizon, quite remarkable, in string theory, is in terms of a well-known physical theory: it is the called the Yang-Mills Theory. So, in a very roundabout way, the physical theories that we developed to study our elementary particles seem to be relevant also to describe black holes, but then we really have to apply them in this quantum gravity regime. So there is some a theory of open strings known as matrices of strings. I have no time to explain the details of it, but the important thing is that this is a working model, an exact mathematical model, that describes to you the physics of quantum black holes, and in fact, out of this, the conclusion is that there is some sense what we call the fundamental layer of physics, namely space and time, gets replaced at very small distances by something more involved and, in the case of string theory, you have a very precise candidate for this more fundamental theory, which is the Large N Gauge Theory.

It is known under the technical name of ADS/CFT Correspondence, the caricature version tells you that all of physics, in this particular model, is equivalent to a theory living only on the boundary of the black hole. So, in some sense, three-dimensional physics or (if you include time) four-dimensional physics, is something that all comes down to this area of the black hole. That is quite an amazing thing because that means that one of the space dimensions, the distance that you go off the black hole, is something which is not really there in the fundamental description – it is what is called an emergent phenomena, something that comes up only in a limited, particularly limiting structure. If you look what this extra dimension is, in terms of the original, the kind of the quantum description, living on the surface of the black hole, you find in fact that this is the Holographic Principle, so it is really in a hologram, which is also a two-dimensional picture that gives you three-dimensional reality. The extra dimension, so to say, that has to be constructed is related to the energy scale in which you probe this two-dimensional system.

Finally, I want to say something about the most radical way in which this is implemented, which is a theory that got quite a lot of attention two years ago by my direct colleague and friend – we wrote many papers together – Erik Verlinde. He took the ultimate consequence of this idea. He said if really gravity is not a fundamental force, if what we call curvature of space and time is, in some sense, just an illusion because, underlying, is this more quantum description, perhaps we should stop looking for a fundamental description of gravity. He noticed there is such a thing as entropic forces, which are in space and also in everyday physics.

There is a famous example of an entropic force which is, for instance, if you take a large molecule, like a polymer or something, or you can even think of a protein, it can be folded in many, many different ways, and if you pick a pincer and you pull on the molecule, you find a certain force. That is the technical description and because of thermal effects, this molecule can be in all kinds of different shapes, and there is a technical description that the force that you feel has to do with the entropy into the system. So there are many forces in nature that are not fundamental forces, that means that there is not a little particle, like the photon for the electromagnetic force, or the gluon for the strong force, the quantum dynamics that is responsible for this. We should not look for an elementary description but we should look for an emergent description. There should be an entropic way to re-formulate all of gravity, and he made a very interesting start in this project.

For instance, he had an embarrassingly simple derivation of Newton's law – it is always nice to tell about Newton's law here I would say, so close to home! But if you look at this as a very element – what happens to a particle if it is in the neighbourhood of a black hole? You can see, by throwing in a single particle, what happens to the entropy. You can look at the temperature of the black hole, which is in some sense a thermal temperature, and again, I will not go into the mathematical details – I am not sure that everybody could follow – but if you combine these three equations in a clever way, you get [$F = ma$].

Derivation of Newton's Law:

$$F\Delta x = T\Delta S$$

$$\Delta S = \frac{2\pi kc}{\hbar} m\Delta x$$

$$T = \frac{\hbar}{2\pi ck} a$$

$$F = ma$$

So, he is doing something very complicated, taking these most fancy new ideas from physics, and out of it producing the very bedrock in which you would think everything was based. So he is really turning things around.

But I think he has a very principal point here because, if you take these ideas, from string theory, from quantum gravity, from his entropic description series, space and time should not be the basis of any of our arguments. Space and time should emerge from what we are doing, so there seems to be something under it. For instance, if you asked the question “What was the very beginning of time?” or “What’s at the very end of time?” it is a little bit like asking, “Where is the beginning of a river?” You can follow it up, get the little mountain stream, and then, at a certain point, there are a few drops of water lying on a stone – is this the beginning of the river? Well, the whole concept of a river does not make sense anymore. What is the temperature of a gas if it only has two or three molecules? The thermo-dynamical concepts stop. So perhaps there should be a more basic description of space and time out of which these emerge.

This goes down to a very deep argument that runs among physicists, which often is phrased as “What is garbage and what is beauty?” So what do physicists like? Often, the word you use describing a physical theory is “beautiful” or it is “elegant”. Where do we find beauty in science? There are basically two schools here. The first school is the reductionist school, and most particle physicists belong to that school. It is where we see a big mess around us, the chaos of life, but if you really go down to the fundamental laws of elementary particles, they are very elegant and simple – only you have to start describing everything in terms of electrons and quarks etc. So that is very neat if you have two or three of these particles, pretty hopeless if you have billions and billions and billions.

So then the idea is you should not look at beauty at the large scale, beauty is at the smaller scales, and in fact, we hope, along that line of argument, that if there is even something more fundamental than the standard model, it will be even more beautiful. Feynman described this in a very nice way. He said, you know, often, in physics, you have a beautiful theory and then some measurements do not fit, and you lose this beautiful picture and you go through a kind of chaotic period of transition, and suddenly there is a bigger picture that comes into mind and it is even more beautiful because it explains more things in terms of a smaller number of ingredients. That is one half of the physics community.

The other half just turns it around the opposite way. Take a glass of water. Now, it has very beautiful properties - it has a temperature, you can do hydrodynamics, it is transparent, you can drink it – but if you want to describe it as a chemist, in terms of ten to the 26 H2O molecules, it is extremely complicated. So the big mess is actually in the small details, and the beauty is in the large scale. The laws of hydrodynamics are beautiful equations, but of course they are only an approximation to this large collection of elementary molecules. So, for instance, thermodynamics is one of the most beautiful theories in physics. Statistical mechanics is a big mess. So beauty is at the larger scale.

Now, you see these two are in conflict, and I think the lesson that we are now learning is that if you really want to understand the full picture of the universe, we have already seen, we are forced, by experiments and results, to combine the largest and the smallest, so in some sense we need some kind of synthesis of these points of view of life. And in some sense, the two things that are competing here is geometry, which is the large scale structure, and quantum theory, which is very different, it is much more abstract, is more algebra than geometry, and both have their own qualities, but if you see in some sense what is the best way to understand these structures, I think, right now, all the evidence, the theoretical evidence, is pointing that quantum theory, quantum information to be more precise, is a more fundamental concept than space-time geometry. So the lesson that you go from the individual molecules to the properties of materials is very similar in which that we go from the individual space-time bits, the bits of Wheeler, to the space-time “it”, namely the space-time geometry, emerging with beautiful equations. In fact, Einstein always said that his two favourite parts of physics were thermodynamics, which had just a few lines and you describe all the properties of all materials, and his own theory of general relativity. I think what you are leading to, that these two things are not only both beautiful and they are analogous, they might be actually equivalent - there might be an equal sign connecting the two. It would be an astonishing effect. I think Einstein would probably feel happy with these conclusions.

But of course, it also leaves you with the enormous question: what is this thing on the left? It might be actually comforting, in some sense, that the basic phenomena out of which everything is made consists of these kind of zeros and ones, which I think is also a good metaphor if you think of our present life. But information might, in some sense, according to this argument, be the very basic layer of our understanding of the universe. Well, this needs a lot of details. I am very much aware this is a very general lecture and I have to remind of an anecdote of Pauli – Pauli, of course, the famous co-discoverer of quantum theory.

There are two quotes I want to mention of Pauli, to his friend Werner Heisenberg. The first one, when Heisenberg discovered the first uncertainty principle, you know, the lectern can sometimes be a particle and sometimes be a wave, he wrote very enthusiastically to Wolfgang Pauli, and Pauli wrote back. This is one week after discovery of quantum theory, and Pauli says: “Well, I think I understand it: if I look with my left eye, I see a particle; if I look with my right eye, I see a wave; if I open both eyes, I become crazy!” You might feel like this!

Or you might feel that there is another anecdote, which, when both are grand men of physics, Heisenberg has a universal theory of the world, and Pauli is in the audience and he listens to the lecture and clearly he is not very impressed with the amount of details of the theory, so he sends Heisenberg a postcard and just has a square on it, an empty square, and he says: “Dear Heisenberg, just to show that I can paint like Titian – details will follow later…”

Thank you!