The Oppenheimer Lecture Series - The Last Lecture

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The Oppenheimer lecture annual series was established in 1998 and is made possible by the generosity of Jane and Robert Wilson, as well as Steve and Ireland Krieger. The series has brought a who's who of theoretical physicists from around the world. Past Oppenheimer lecturers have included C Yang, Freeman Dyson, Helen Quinn, Charlie Kane, Andre Linda, Murray Gelman, Stephen Hawking, Kip Thorne, and Marvin Cohen, who's joining us via zoom I believe. Many prominent theorists in the fields of particle physics, condensed metaphysics, astrophysics, cosmology, and AMO have stood where I am standing today. Robert Oppenheimer was born in 1904, growing up in an upper class family in Manhattan. He graduated from Harvard, majoring in chemistry, entered Cambridge, the other Cambridge across the Atlantic in 1924 as a graduate student, hoping to work with Ernest Rutherford, who many of you may know is the second most famous New Zealand physicist. He was then leaving in 1926, and so Oppenheimer finished his PhD with Max Born in Gotegoan. He published more than a dozen papers while with Born, mostly focused on the new theory at the time of quantum mechanics, this included his most famous Born Oppenheimer approximation that simplifies molecular physics by separating slow nuclear motion from the faster electron motion. More than 90 years ago, in 1929, after two years of post-doctoral study, mostly in Europe, Oppenheimer returned to the US, he accepted an associate professorship right here in Berkeley, where he remained for nearly 15 years.

During this period, he published his famous paper with Volkoff establishing the Tolman Oppenheimer Volkoff limit on the maximum mass of neutron star. The mass above which star must collapse into a black hole. He also developed the theory of that collapse and black hole formation. Both topics are of keen interest today as many of you may know with the recent observation of gravitational waves from black hole and neutron star mergers. Okay. At Berkeley Oppenheimer's group, typically eight to 10 graduate students and half a dozen postdocs, met with Oppenheimer every day, with Oppenheimer probing them about their progress. Hans Bethe noted that probably the most important ingredient he brought to his teaching was his exquisite taste. He always knew where the important problems are. The scientific leadership of Oppenheimer demonstrated at Berkeley complicated his later life and his role in science as many of you know. In 1942, he was selected to lead world war II's Manhattan projects, engineering lab cited at Los Alamos, near a ranch Oppenheimer owned. His leadership of his effort culminated in the successful Trinity test and later the political decision to use atomic weapons against Japan. A decision that troubled Oppenheimer for the rest of his life. After world war II, Oppenheimer became the public face of science and technology featured on the covers of time and life magazines. This period of his life came to a close with a controversial loss of his security clearance in 1954. That's his badge shown to the right there. A time when the new cold war and McCarthyism was stoking fears. There was some resolution about a decade later when President Kennedy presented Oppenheimer with the nation's Fermi award. My notes say Kennedy, but the picture clearly shows Lydon Johnson, I think, but anyway, one of them definitely gave him the award. Oppenheimer's legacy at Berkeley is a simpler one summarized by a plaque on the fourth floor of physics, south hall, with another quote from Hans Bethe.

"In these corner offices, 1929 to 1942, Jay Robert Oppenheimer created the greatest school of theoretical physics the world has ever known. Berkeley physics strives to continue this legacy today." So with that introduction, it is now my great pleasure to introduce my colleague from UC Berkeley physics professor Raphael Buso to introduce tonight's Oppenheimer lecturer, Dr. Lenny Susskind. - Thank you, James. Well, it's a great pleasure and honor to introduce Dr. Leonard Susskind. Lenny is a legend. He's also a friend and a mentor, to me personally. He has made many great discoveries, and don't worry, I will not tell you about all of them. He's won great prizes, like the soccer ride prize. What I wanna talk about is how that's really just half of the picture. Lenny, more than almost any other great theoretical physicists that I've had the privilege to meet has taught us how to think, how to pick important topics, how to tackle them. And the best way that I can try to convey that is by telling you the story of how I first met Lenny, which he probably doesn't actually know. This was in 1994, and I was an undergrad, I was trying to decide between grad school at Stanford or in Cambridge, England, I didn't get into Berkeley. Is anybody here who... No. Anyway, so I went to Stanford to sort of check the place out and my hope was to meet with Andrei Linde, but he had broken his legs so he couldn't meet with me after all. But this guy comes running in, wearing running shorts, sweaty shirt. And I tell him, I'm thinking about grad school, I'm interested in quantum cosmology and black holes and so on. And he sits me down and he gives me this very clear lecture about how Stephen Hawking is completely wrong about black holes. And this whole idea of the wave function of the whole universe. There's nobody who can see the whole universe, doesn't make any sense. And this completely shocked me.

I'd already spent a little bit of time in Cambridge and it's a place that definitely sees itself as the center of the universe and shall not be criticized. So this was remarkable. And I went to Cambridge anyway. But, what Lenny had explained to me, he explained in such a way that it stayed and it planted a seed. And even though I became Stephen student, and that was great, it was a wonderful time. I came to realize that Lenny was probably right about black holes and Stephen Hawking was wrong. That information really does come out of black holes and is not lost. And, before you knew it, Stephen Hawking decided that Lenny was right about black holes. Now, this is just an example of, I think how Lenny operates. He's good at making people think the right way about something, he's good at guiding the field and for generations of physicists coming and going, he has guided us in the right directions. He's championed sometimes unpopular ideas, and topics that people wouldn't touch. And he's got a stellar record on those picks. Now, how did he do that? I don't really know how to explain it, it's some sort of irresistible clarity in the way he thinks about things and conveys those thoughts. It's a radical inevitability. It's some contradiction in... You hear it at once it's like my goodness, this is completely crazy. And yet you realize there's no other option. And fortunately, I don't have to explain it to you because we're about to hear Lenny explain some things to you. So I welcome professor Leonard Susskind. - Okay, so your slide deck, which is where? There. - It's very nice to be here. - How do we get that? - The last two and a half years? I haven't been no more than 30 miles from my house. - I dunno how to- - I'm now, about 35 miles from my house. - That one. - Wonderful. Okay. Good. Okay. So Thank you, Raphael. I've known the name Oppenheimer since 1945 when I was five years old. sometime after August 6th, I think it was, I asked my grandfather, "grandpa, what's an atom bomb?" He said that he didn't know how it worked, but he did know the one most important thing.

He said it was a giant bomb that had been built by a Jewish man named Oppenheimer. That's all I know about Oppenheimer for about 15 or maybe a little more years, when I started to read his papers, his physics papers. In fact, I did read a number of them and one of them had a great influence on me, a paper with a young, I'm not sure he was a student or just a young physicist by the name of Harland Snyder, a brilliant young physicist that gave rise to the modern theory of black holes. Even if it's not explicit, everything in my lecture today, rests on the foundation that Oppenheimer and Snyder laid in 1939, which by the way was a year before I was born. Okay, let's begin. I maintain that, that the biggest puzzle about physics is that it exists at all. I don't mean that the laws of physics exist or that they are precise and mathematical. I mean, the fact that an animal who's closest relative is the chimpanzee was able to ask about these laws. There he is, up there. But was also able to navigate through a sea of wrong ideas and eventually hit on relativity, quantum mechanics, the standard model of elementary particles and more. That is a absolutely remarkable fact, that is not a physics fact, it's probably a biology fact, but it just blows me away. What are the tools that our ancestors used? Intellectual ancestors? I don't mean the monkeys. I mean, Newton, Einstein and so forth. What were the tools that they used to be able to answer these questions? Well, there were theoretical tools, the thought experiments, apparent conflicts of principle, paradoxes, and of course mathematics. but some people would say the most important tool was of course experiment. Today, we're going to talk about a subject, quantum gravity, which is so remote, the scales of distance so infinite decimal, the energy is so enormous, that direct experiment is entirely out of the question, at least for now.

The phenomena, which are at the intersection of quantum mechanics and gravity. Quantum gravity, to give it a name. So we theorists are on our own. Can we make progress? Well, it seems that we have made serious progress over the last two decades. Maybe even revolutionary progress. Okay, as I said, the phenomena are so remote that the possibility of experiments is outta the question and it means we're really on our own. We have made progress, and I'm gonna tell you some of the little pieces. I'm not going to give you the whole story I couldn't possibly, but I'm gonna try to give you some feel for what some of the pieces have been that I think are adding up to a revolution. Okay. So where are we? The whole subject of quantum gravity probably goes back to the first day that anybody thought about quantum mechanics and thought about gravity. But the modern era of it, I think started in 1958 or sometime around then when theoretical physicists asked the question, should we quantize gravity? Now, what does quantize mean? Quantize was an expression which meant a procedure, a procedure that you do on a classical system. The classical system could be a harmonic oscillator, it could be an atom, it could be electrodynamics, ordinary electrodynamics. The procedure which, if you know about that procedure, you recognize the equations. If not, it doesn't matter. There are equations and the founders of the subject, Paul Dirac, Feynman, Dewitt, Weinberg, Wheeler, Hawking their attempts were organized around trying to describe scattering processes. Processes, where particles come in and particles go out, they interact under the influence of gravity and the here and there they may emit some gravitational waves. Gravitons. They invented Feynman diagrams for gravitation. Well, it was a disaster. It was a disaster. Everything they tried to compute came out infinite or came out meaningless, came out nonsensical. And that led to what I would call an era of angst and confusion, a time when it just did not look as if quantum mechanics and gravity were compatible.

Now, how could they not be compatible? They have to be compatible. The world has both. And we can't live in a world where of inconsistency. And that was then, how do you fit them together? Can you fit them together? They looked impossible. Today the situation is different. Today, as far as we can tell, not only can gravity and quantum mechanics fit together, but it's almost as if they were the same thing or two sides of a coin, a single coin. I'm going to tell you a little bit about some of the things that went into that. I always start with digression I'm a great digressor. I digress all the time. I'm going to digress about something. You've all seen holograms, what is a hologram? You've probably all seen them. The first holograms was something like this. You had a region inside, a cavity of some sort, and the cavity not a cavity, just a round region. And the cavity, the surface of the cavity was a film, a photographic film. And if you looked carefully at that film, even through a microscope, all you would see was little scratchy, meaningless, rubbish, noise. It seemed to encode nothing, nothing recognizable. On the other hand, if you shined light on it, of the right kind, what is called coherent light, all of a sudden vuala, an image would form, but a three dimensional image, right in the middle of this cavity, a three dimensional image of whatever it was that had been photographed. What is a hologram? From an abstract point of view, a how a hologram, is a two dimensional mathematical representation of a three dimensional portion of the world. Now, how do you manage to take a three dimensional thing and map it into two dimensions? Well, it's possible, but it is always at the cost of the two dimensional image being, looking like a random harsh. How you put it back together again, that maybe just shining light on it, or it may be some much more complicated mathematical procedure, but that's what a hologram is.

And what you can say about a hologram is that things are not where you think they are in the hologram, the information, it's called the information of what is in the hologram is in the film. The image is in the bulk. What we today call the bulk, things or the information encoding things are not where you think they are. I want you to keep that in mind. Now let's come back to quantum gravity, in the 1990s, this was the period when Stephen Hawking and I were having our fun debating and Raphael was a student. Thought experiments, principally initiated by Stephen himself about black holes led to something called the holographic principle. What was the holographic principle? And what is the holographic principle today? It's the idea that a region of space with everything in it, it could be astronomical space, it could just be this room or even the whole universe that the information encoding, everything taking place in this three dimensional world is encoded on the boundary of that region as a kind of quantum hologram. It's of course impossible for me to describe the mathematics of the quantum hologram here. And we'll try. But that's the message. And again, things are not where you think they are, or at least things are not where the information which is encoding them would lead you to believe they are. Okay, let's come back now to this idea that gravity and quantum mechanics may be so closely related that they really are just two sides of the same coin. The evidence for that, is a whole bunch of parallels between gravitational phenomena... We'll talk about what that means in a moment. And quantum phenomena. Things that we had no idea were connected. Things from two radically different fields of physics are turning out to be parallel to each other and perhaps even not just related to each other, but the same thing. The connection is through this holographic principle, the gravitational phenomena of the phenomena which are like the image, the three dimensional image.

The encoding of that three dimensional world is in the form of the quantum mechanical hologram. The correspondences, are correspondences between the two of these. So I will give you some examples. Let's go to the most primitive or basic of gravitational phenomenon. You all know why that is. If you've fallen out of bed, I've fallen outta bed a number of times regularly, you know what gravitation is? It's falling, falling in a gravitational field. And if I wanted to express it abstractly, I would say that the gravitational force just like any other force, is a tendency for things to accelerate. In this picture here, the apple is accelerating. It's accelerating downward, caused by the gravitational field of the earth. You can rewrite the equation F equals MA of course. You can rewrite that, as F equals the rate of change of momentum. The momentum of the apple is increasing as it falls. So you can say that falling, is the tendency for momentum to increase in the presence of a gravitational field. That's one side of the coin, the falling side. The other side of the coin, the quantum side is something so radically different, that it's hard to imagine that it has anything to do with it. You take some quantum system now, this quantum system I'm imagining is the quantum system encoding the hologram. This bunch of squiggles and random looking bits of information out at the boundary of the region of interest. And you come along and you tap the system, you perturb the system, you might hit it with an extra electron or you might do, whatever it is that you do to it. At some spot, you perturb the system that perturbation, this is a quantum mechanical fact will start to spread throughout the system. It's influence will spread throughout the system like an epidemic. You touch one qubit, if you know what a qubit is that qubit will touch a few more qubits, few more qubits will touch a few more qubits. And the effect of perturbing the system will spread.

There's a notion of size, it's like the size of an epidemic. The size of an epidemic simply means the number of sick people and the number of sick people has a tendency to grow. Here's an example for the experts on quantum computation. If there are anybody know about quantum computers? Nobody, good. Okay. Then this picture doesn't mean much to you, this is a quantum circuit and it proceeds from left to right. If you perturb it with a, with a green qubit, that perturbation will spread throughout the quantum computer. And that's the phenomena of scrambling of information scrambling. Now, what on earthed does this have to do with falling? I'll give you an example. It comes from a setup called a dS/CFT that may not mean anything to you. It's fine. It doesn't matter. Let's lemme just, oh, I just realized I have a, a laser point they're built into here. It's not really a laser pointer. Yeah, good. All right. What is this? This is the boundary far away, the boundary encoding the hologram, the bulk of space, the interior is in here. Imagine coming and perturbing the hologram, perturbing means just hitting it or something. That information that you've done so starts to spread and starts to spread throughout the hologram. And there is this notion of the size of the perturbation. You can calculate these things. And the calculation as I said is purely quantum mechanical, maybe a bit of quantum feel theory, but no gravity. And what do you find? You find that the rate of change of size in this set up, is exactly equal to the mass of an object, which was created at this point times, the gravitational acceleration. These quantities here, you get from elsewhere, but they're well defined in the context. And what does it say? Well, what would gravity say? Gravity would say that the time derivative of the momentum of the particle that's falling is equal to mg. And so we see these two different fields of physics entirely different coming together and giving rise to an equation, I don't know if Galileo would've recognized it in quite this form, but it was Galileo's equation.

And in order to make sense of it, you have to believe that momentum of the object which was created is simply the size of the perturbation. Now, you may not understand that. You may say he's talking gobbledy gook. And the main thing that I want you to get from this is, again, this correspondence between gravitational things, this unexpected correspondence between gravitational things and quantum things. Here's another example, instead of a flat plane being the hologram, we can imagine the hologram is a sphere surrounding some place at the center of the diagram, the center of the picture, there might be a black hole or planet or other mass. If you do the same calculation in this context of calculating how the size of a perturbation grows again, purely quantum mechanically, what do you find? You find the marvelous formula that the rate of change of the size, the mass times, the acceleration of the informing object is just equal to the product of the two masses, Newton's constant and the distance between them squared. In other words, Newton's law of gravity. Quantum mechanics, the growth of size. Gravitation, gravitational attraction. To me, that is very stunning correspondence. Okay, let's come hunt to black holes in paradoxes. It was a famous paradox of Stephen Hawkings. I'm going to oversimplify it, not just Stephen Hawkins paradox, but a later paradox called the firewall paradox. Please, if you're a theoretical physicist, don't shoot me for the way I explain this, 'cause it's gonna be oversimplified. The black hole paradox. We have a black hole, the horizon of the black hole is simply this circle here. And we throw something into the black hole that has some information an encyclopedia. And I'm gonna call that encyclopedia A, there's no escape from a black hole, or at least as far as we knew in the 1990s, there was no way that anything can escape from a black hole but, the black hole can evaporate.

That was something that Stephen Hawking discovered that black holes can evaporate and they can shrink. At some point they shrink enough that something strange happens. Namely, there is not enough information, enough area, enough whatever it is in that remaining black hole to encode the encyclopedia that you threw in. It's called the page point and all of a sudden the encyclopedia simply cannot be there anymore. Where is it? Or where are its bits of information? They're in the Hawking radiation? So the encyclopedia gets transferred or the information of the encyclopedia gets transferred to the radiation. That's a quantum mechanical principle that's, we've known about for a long time. And if you take that radiation, imagine somebody takes that radiation, grabs all the photons puts them in a box and squeezes that box down to some small box somewhere. Then what this is telling us, the quantum mechanics is that the encyclopedia again, I emphasize by that, I mean the bits that comprise the information in the encyclopedia is transferred from the black hole to the radiation or to the black hole that the radiation might have been compressed into. In other words, as the black hole shrinks, it cannot hold any information. And if it can't hold any information, nothing can fall into it anymore. And one says that there was a firewall at the horizon, firewall doesn't mean in the sense of burning up. It means in the sense of an information firewall that no information can fall into the black hole anymore. If every time you try to do so, it pops out and it appears far away in the radiation. That's the idea now. This idea of a firewall was very, very badly at odds. Was what we knew about general relativity. General relativity always said that you can always put things into the black hole and they will simply stay there. So this led to this paradox, the so-called firewall paradox. Would say it this way, either there is a firewall or sometimes call... Raphael, were you the inventor of A equals RB? I think he might have been.

Yes. I think he was, as a matter of fact. The idea is a generalization of the holographic idea that things are not where you think they are. And that in fact, the encyclopedia, which is in fact behind the horizon of the black hole, but it's bits of information are found far away in the Hawking radiation. Don't worry about what A and R B stand for. What it says is that the information comprising the black, the thing inside the black hole is far away, far away on Alpha Centauri in some other system. In other words, it's an extreme version of this holographic idea that things are just not where you think they are. Well, that seemed too crazy. I think even Raphael thought it was too crazy, it did seem too crazy. But one thing ,it seemed to suggest that if somebody far away manipulated the radiation in this box, it would immediately have an effect on the interior of the black hole an effect, which if somebody jumped into the black hole would detect what was done far away. And that seemed totally inconsistent where the idea that close things can affect close things, but they can't affect far things. Well, it needed a new idea, resolving this puzzle required a new idea. And the new idea is called E R equals E P R. ER stands. Well, let's first do E P R. How many people here know the, who are EPR stands for? Good, a good fraction of you. Good. It stands of course, for Einstein Podosky and Rosen, but it also is the phenomena of entanglement, quantum entanglement. Now I'm not going to tell you exactly what the quantum entanglement is. It's what Einstein called spooky action at a distance. I'm just going to tell you a very, very simple version of it. Two things, there could just be two electrons or they could be two nuclei, or they could be two macroscopic objects are entangled if by measuring one of them, you find out certain kinds of quantum information about the other one, no matter how far away that other one is.

Let's just call that entanglement. Now, all my physicist friends know that I'm being oversimplified, but there is this phenomena of sharing information between two different distance systems that's called EPR entanglement. And it's a very mysterious phenomenon. And I'm not going to explain it now. We'll just say it exists. That was the year 1935 when Einstein Podolsky and Rosen discovered, or at least let's make it simple, discovered entanglement. It was incidentally a very good year for Einstein. Einstein, I think had three really good years. 1905, when he discovered, especially when he discovered all of modern physics, except for gravity, except for the rules of gravity. 1915 or so when he completed the general theory of relativity and understood gravity. And 1935, which is much less famous in which he discovered this phenomena of entanglement, but the same exact year, he discovered something else called Einstein-Rosen bridges, Einstein, or sometimes called wormholes. Wormholes are a solution of Einstein's equations in which you have two black holes, far away from each other with a kind of tunnel of space between them. You can't see that tunnel of space. It's some interior space that can't be seen, but the two very distant objects are connected by a, I call it a tunnel, I call it a bridge, I call it a wormhole, all the same idea. You've seen these things in science fiction, people jumping into wormholes and so forth. I always thought it was nonsense, but not completely. What's the idea?. If you could go as fast... if what it sounds like is you can jump into one black hole over here and pop out over here. Well, we'll see that you can't do that, but nevertheless, that's what a wormhole resembles. The science fiction idea of a bridge between very distant places. Now, what does ER, that's the bridge Einstein Rosen bridge have to do with EPR other than they have two letters in common. Nothing before 2013, nobody and I'm absolutely convinced that Einstein was a among that nobody had any idea that entanglement and wormholes or Einstein Rosen bridges had anything to do with each other.

And after 2013, they had everything to do with each other. In fact, the idea goes with the acronym, ER equals EPR. You could call it P equals one, but nobody does. ER, the idea of a bridge between distant regions of space, and the idea of entanglement are the same idea. So I'm gonna show you a little bit about how that works. The rectangle here is supposed to be space, a big region of space. Over here on earth, we have a bunch of particles, far away on Alpha Centuari we have another bunch of particles, two clouds of particles. Those particles have never been in contact with each other, they don't know about each other, they're completely separate with no prior interaction between them. I'm going to take this sheet of space and fold it over, not because it's folded over, but just why I want to draw it that way to make a point. But it is still true that this cloud over here is far from this cloud, because you have to go around this long way to get there. What happens if you let those clouds of particles, collapse, shrink, they form black holes. That's where a black hole is. It's the shrinkage and collapse of a star, for example, these could form a star eventually. And after a star, they could form black holes and those black holes will be completely separate from each other with no connection between them. On the other hand, let's do something else now. Let's take a bunch of entangled electrons or a bunch of entangled particles. Half of them are over here and half of them are over here. Now, how do you create the green line here just indicates that this particle is entangled with this one, this particle is entangled with this one. No, not that one. This one. How do you create such a situation? To create it you have to create the entangled particles near each other. You can't create entangled particles far from each other. You have to bring the particles together.

You've got to let them interact with each other and they will become entangled. But once they're entangled, you can take the half of them. That's down here, separate it. Well, let's say we take this half of them and bring them all around here so that we wind up with two clouds of entangled particles. Now we let gravity do its work. And when gravity does its work again, it creates two black holes, but the black holes are now connected by an Einstein-Rosen bridge. In other words, entanglement and worm holes are in some sense, the same thing. Two black holes which are entangled were necessarily have a bridge between them, two black holes which are untangled will not. This is what's called ER equals EPR. And it was a major discovery. It seemed ludicrous at first, but it very quickly caught on and is now part of the standard law. What can you do with it? Okay, so let's imagine now that we do have such a wormhole connecting two very distant black holes. One of them Franklin, has control over. Control means he can do things to it. He can jump into it if he wants. The other one, Linus has control over as control over and they're very far away. One is on alpha Centauri the other is on earth, but they have this Einstein-Rosen bridge connecting them. Well, with enough care and enough fine tuning they can arrange these black holes so that they can each jump into their own black hole, and in a very short period of time can meet at the center and shake hands. What they cannot do, at least without some further considerations, which I'll come through if I have time, I may not have time. Linus cannot jump into one pass through and come out the other one, that can't happen. Now, the fact that it can't happen is both known from the quantum mechanical point of view. It's called a no signaling theorem for entanglement. And for worm holes it's called, the non Travers ability of worm holes, the impossibility of traversing through them. And it turns out those are the same phenomena, one quantum mechanical, the other gravitational.

Now let's come back to A equals R B. The encyclopedia A in black hole number one or in left hand, black hole here is encoded in the radiation in region two over here. Our problem before was that sounded crazy because somebody manipulating the radiation over here could perturb what's inside the black hole in just such a way that somebody who jumped into this black hole over here would detect that a very, very distant observer had done something to this group of photons over here. That sounded outlandish. But now we know that if these photons over here are entangled with the black hole, which they will be, that an Einstein Rosen bridge and from outside, you can't see that Einstein Rosen bridge, but the Einstein Rosen bridge will open up. And so anything anybody does over here will affect what's behind the horizon of the original black hole. In other words, A equals R B makes perfect sense. Again, it has to do with this basic idea, that information is not where you think it is. This is a radical example of it. What about the wormhole side of it? How can it be? Why should it be that somebody who goes into one black hole and alpha Centuari can't get through the wormhole and come out? Well, one end of the wormhole is in New York, the other end is in California. Think of it as a tunnel between the two places. Why can't you drive through that tunnel? And the reason is that Einstein-Rosen bridges, and this is a gravitational phenomena, tend to stretch and expand with time. That's the solution of Einstein's equations, gravitational equations, wormholes grow. So, who was it? Franklin, I can't remember Franklin or Linus. If Linus tries to drive into the New York side, he will encounter the fact that the worm hole is growing. And in fact it will grow so fast that he cannot outrun the growth of the worm hole and will simply navigate through to the other side and come out the other side. That's the non traverses ability of wormholes.

You can't even send the light signal through, because even a light signal will not go fast enough to outrun the growth of the wormhole. That's the gravitational side of it? Is there a quantum side of it? Yes, there is. And I don't have time to tell you what it is. I will tell you what it is, I don't have time to explain it. But I'll tell you that it's a computer science concept, it's called the growth of complexity. The black hole quantum state of the system is becoming more and more complex. It's very much like this information scrambling that we talked about, having to do with falling. The quantum state of the wormhole evolves, it becomes more and more complex, and that complexity translates into the growth of the wormhole. So these are all these very, very remarkable correspondences, which tend to make us think that there, not just that there are deep connections between quantum mechanics and gravity, but at some level, as I said, I'll say it again, there are two sides of the same coin. Okay, so, we have the idea of a quantum hologram encoding information, which could be far from where the object that it's encoding is. And what is the other side of the coin? The other side of the coin is, gravity. I like this picture, it's my favorite one of all. Okay. Whoops! What happened here? Oh, my, this are totally different subject. Let's see if we can get it back, up in my lecture. Good, here we. All right, now let me address. Let's see how much time do I have Raphael? I'm I running out of time? 15 seconds? - 15 minutes. - Oh, 15 minutes I only need 15 minutes. Lots of time for questions. Okay. There are criticisms. Oh, incidentally we might point out that most of these ideas grew not just out of a combination of quantum mechanics and gravity, but string theory. How string theory got into it, I haven't really said very much about. But let me tell you that all of the precise examples, all the mathematically precise examples of this correspondence tend to come from systems which were invented or discovered in string theory.

A string theory, quantum gravity has been the victim of an enormous amount of criticism. The criticism, which first of all, thing is unjustified, but what does it have to do with the criticism? I would say, stems from the fact. And I think it is a fact that good science almost always spreads its influence far and wide into many fields of not just physics, but even outside of physics and in particular into engineering, into technology. And that's a pattern that we've seen over and over and over again, special relativity led to nuclear energy. General relativity, we use it for navigation by satellite, believe it or not. Quantum mechanics, the list of technological advances and quantum mechanics was not invented by people trying to do technology, was invented by people who were curious about the atom. Quantum mechanics among other things, it led to the MRI machine. But so many things that I have that the list would go on and on. Quantum electrodynamics trying to understand the quantum mechanics of electrons and photons and particular photons, led to the laser. Or at least as closely connected with the laser and so forth and so on. What about Quantum gravity, general relativity and its connection to quantum mechanics? It seems so infinitely remote with no connections or applications to the rest of science. It could be that that's true. It could be we're just stuck with that, but that has not been what is happening. First of all, this connections between quantum mechanics and gravity have led to new insights into strictly phenomena, which seem to have nothing to do with gravitation. For example, the surface of a black hole, the horizon of a black hole, behaves as if it were made of a fluid. That's something that general relativist discovered a long time, but not just a fluid, but a quantum fluid, whatever that means. One can use the fact, by knowing enough about black hole physics and knowing enough about general relativity, you can compute properties of fluids that were too hard to compute, otherwise.

Here's one example of something that was inspired by the connection between fluid mechanics, black holes in quantum mechanics. It's a bound on the viscosity of fluids. Now that doesn't seem to have anything to do with either of those subjects. Well, it's a little bit quantum mechanical. It is quantum mechanical. Eta is a viscosity of a fluid. The stickiness of it. S on the right hand side is the entropy per unit volume of the fluid, the heat per unit volume. What was discovered in the context, not discovered by people doing fluid dynamics, people comparing properties of black quantum mechanical black hole horizons with fluids is that the viscosity is always greater than equal to some number. That includes H bar that includes the quantum constant times the entropy density. Will that have impact into fluid dynamics and into probably... There are things called strange metals. Strange metals are a form of matter, that was discovered by condensed metaphysicist. Are they important in technology? I don't really know, but they were discovered about 30 years ago and they were metallic systems, which behaved just differently than ordinary metals. It's turning out that those strange metals are mathematically identical to certain special kinds of black holes called Extremal black holes or near Extremal black holes. Both sides are quantum mechanical, one side is also gravitational extreme of black holes, the other side is the pure quantum mechanics of certain materials. Information scrambling, the thing which I told you, accounts for the falling of the apple, as it accelerates in the gravitational field. Information scrambling is an important thing in quantum computer science. The information scrambling from black holes led to a bound. Again, another bound that a certain constant called the tapping exponent in information scrambling is always less than some other constant.

That now is considered, a reliable fundamental bound on how fast information can spread through a quantum mechanical system. I told you that Linus cannot get through the wormhole. Well, I was a little bit too pessimistic with a little bit of help from something called the exchange of classical information. These little purple dots being sent from one side to the other, that's just ordinary Morse code, for example. But has no information about Linus or about anything else inside the wormhole with a little bit of help from a little bit of classical information, you can slow down that growth of the wormhole. You can slow it down enough so that indeed Linus can get through it. That phenomenon, which was discovered in the context of gravity and quantum gravity, has led to a new protocol and new experiments for quantum teleportation. Quantum teleportation is a real thing. You can teleport information, what it means, and you can't exceed the speed of light, but you can send information in a way that is completely hidden, 100% hidden, cannot be decoded by an eaves dropper. And so it's led to new protocols for quantum teleportation. Experiments are now being done to confirm that this can happen not in black holes, but in quantum computers. I'm not allowed to tell you that the experiments are successful because I promise not to mention that they're being done and that they're working out successfully. So I won't, quantum complexity theory, the growth of worm holes, the whole idea of gravitation being controlled by the growth of complexity has led to many new insights into how complexity of quantum systems evolve. We've seen advances coming from gravity in error correction. Error correction is the big hangup in trying to build a quantum computer. It's too easy to make errors in a quantum computer. You have to error correct for them. And a whole new insight into error correction has come from thinking about gravitational systems again. And finally, in the hands of one of my favorite physicists, OwanMolsinner.

Much of what we're talking about has had a very interesting influence in cosmology, in inflationary cosmology. So far from being a totally isolated thing, outside the framework of any other science. This quantum gravity is beginning to have an effect, which let's just put it this way, condensed metaphysicist and quantum computer physicists and theoretical cosmologists are being forced to learn, what AdS/CFT means, and they are learning it. They're learning it and using it. So this is exciting. This is a very, very exciting period in the development of physics. It is also one which is very, very difficult to explain to a general audience. When you give a lecture like this, or what do Lincoln say? You can please half of the people, half of them blah, blah, blah this time. Well, you can please half of the audience, so half of the time and so forth and so on. I think the real truth is an lecture like this, you're lucky if you can satisfy any piece of the audience even a little bit, because the ideas are complicated, they're difficult and so forth. You do your best, you do your best to try to explain. And I've tried to explain as well as I can. I hope you have gotten something out of it. I hope there's at least one person who has gotten something out of this lecture. And I thank you for listening. - Okay, we have some time for a few questions, from the audience. I also have some from zoom. Would anyone like to ask a question? Well, I got a couple on zoom, so, oh. - I'm a little bit harder to hearing. - Okay. I'll speak up. - It May be necessary to. Okay, Try it. - Okay. How are you? There's an experiment going on using drones, to detect quantum waves. - Drones. - Drones, - Drones, the stuff lying around in Ukraine. - Bombs? Drones, drones, drones. - Yes drones. And they're used, they're planning on, there's experiments going on and using these to detect quantum waves. How are they? okay. I guess the it's an interesting- - I have no idea.

- I'm interested in the drone part, so, okay. That's, I'm sorry. - You tell me. - Well. - I never heard maybe. - Okay. - Okay, we have a question across that. - Hi. Hello. Just out of curiosity. Did you draw the Charlie brown drawings yourself? Or did you find those. - I'm having a real difficulty hearing. Can somebody closer? - Did you draw the cartoons yourself?

- Can I draw the? - The cartoons? Did you draw those cartoons? The peanuts cartoons? Did you draw them yourself? - Oh yeah. - Some of them are just copy, but they were all hand drawn by me. Yes. My first ambition had been to be a painter, not a house painter, a picture painter. The problem was ,I had no talent, whatever, or at least my talent was, maybe being able to draw a Charles Schulz cartoons. But I really wanted to be Picasso, didn't work out. - I have a couple of questions for online. How can a wormhole grow faster than the speed of light? - Well. Locally each piece of it is growing, the rule is not that one thing can't exceed the speed of light. It's one thing cannot pass another close by, at faster than the speed of light. The universe, For example, in some sense grows faster than the speed of light. The accelerated expansion of the universe tells you that if you're far enough away, just the hub law, that things will be moving away from you faster than the speed of light, but it does tell you, that you can't get information from behind, from that far away. And that's what creates a horizon, that creates a cosmic horizon. The same is true here. The wormhole can grow, but if it's growing that fast, you simply, you can't get through it for one thing and you can't receive signals from far away along the wormhole, unless this idea of classical information being sent back and forth, can come and slow the growth of the wormhole. And that is something that there's mathematics for it and in some way, it's being tested in laboratory, not in real wormhole, but in entangled, quantum computers. - First of all, fantastic lecture.

It was great, but I'm not gonna admit. I'm not gonna state that I understood. - No, of Course. - But, I mean, one of the, as a person who happens to have worked on strange metals and thought a little bit about quantum computing, how much of the connections between the quantum gravity and everything you've been saying and these other fields that some of us work on, is because of the mathematics discovered in the process of working out theories, string theory and working out theories and how much is some deeper connection between the phenomena? - Okay. I think the connections are deeper. Certainly that's part of it. Just, the mathematics seems entirely similar. You probably know about the such FDA kata theory. That's an example. Yeah there, but a lot of the physical phenomena experienced in that system are identical to the physical phenomena that you would expect in a near extreme of black hole. So I'm hesitant to say that it's just the mathematics, so I don't think of it, I think there is a real physical similarity, if that's what you're asking, I think there is, yeah. We'd have to sit down and talk about that obviously, but a. - I have another question from online if I may? Yeah. So, can you say a few more words about the growth of quantum complexity and how it corresponds to the non traversability- - So many words you wouldn't believe it and I have, but I'm not sure this is the venue for it. Quantum complexity, Well I'll tell you what quantum complexity is. First of alllemme tell you what complexity is. Complexity means lots of different things to different people. You might think, for example, a beautifully designed building or something, or a beautifully designed car is complex. No, it's less complex than almost anything you can think about in that sense. Complexities used in other words, I have a very complex relation with my mother-in-law. Unfortunately I had a well, but fortunately I had a very good relation with my mother-in-law, but you could use the term that way.

In fact, a very special thing is meant, complexity if you have a given problem, complexity is a measure of the shortest number of steps to solve that problem. Let me give you an example, theorem improving, you start with a bunch of axioms, and now you have some theorem that you think might be a theorem and so you go to try to prove it and you prove it. Okay, It took you a certain number of steps. That number of steps might not be the cheapest and least number of steps that it takes you to prove the fear. And what I mean, the steps are the use of the logical axioms together with the rules of logic, each one being used once is a step. Your proof might involve 550 steps. The complexity of the theorem is a measure of the least possible number of steps that it would've taken to prove the theorem. Another example from quantum mechanics or quantum computation is you have a quantum computer and you're going to put into it some simple state, and you want to run that computer and get to another state, which may have some interesting information in it. Okay. Quantum state of a bunch of qubit or something like that. You can think of different ways of getting there. There are different roots, different series of gates, different series of processes that could bring you to that, target state. The complexity of the state is a measure of the fewest number of simple operations that can get you there. That's the notion of complexity. Now that's exactly the notion that's used in this wormhole situation. The wormhole grows, which is simply another way of, well, which means that the quantum state of the two black holes evolves with time. It's a general feature that complexity increases with time. In other words, you go to states, which are harder and harder to get to, which would take more and more steps to get to them. And curiously, interestingly, there appears to be a connection between how complex the quantum state of the black holes is and how big the wormhole is? That seems to be something that's fairly well confirmed by now and so it is believed that the growth of the interior of the wormhole is equivalent that's the gravitational side, that's the general relativity side, equal to the tendency for quantum complexity to increase with time for a complex, for a chaotic quantum system.

So I'll have to leave it at that, because as I said, I could say a lot more, but it would take more time than we can expend. - That Was great. - Hello. So I was wondering, since you said that the center of a black hole, or at least the holographic surface of the center of a black hole acts like a fluid, would solving- - The horizon, Which is a kind of holographic surface, yes. - Okay. So if it acts like a fluid would solving the Navier-Stokes equation, be a step forward to figuring out what happens at the center of black? - Frankly, I think it will happen the other way that people will be able to solve the gravitational equations for this fluid and make steps that direct attack on the Navier-Stokes equations would be too hard for. So my guess is it will happen the other way that not solving a Navier-Stokes equation, won't teach you that much about black holes, because I think it's just too hard to do, but solving black hole equations, which are a lot easier, because they're just, Einstein's equations, might very well teach us a lot about dynamics of fluids. That would be my best guess as to which way the information will flow there. But there are other experts on that subject here and I think you're an expert, right? Yeah. Yeah, he doesn't know me? I don't know who somebody's in there. - I got a question here. I don't if he knows who? Anyways. I was wondering if there is a relationship between the surface and the entropy? - Between the What? - What's, here. Hello. I was wondering if, so you mentioned there is bound on the viscosity of the black hole and the entropy. So since the viscosity somehow seems to be on the surface of the black hole, is there a relationship between the surface of the black hole and the entropy? And if so, or why? - Black holes and horizons have entropy, they have a uniform entropy distributed over the horizon.

They also have viscosity. So it was realized by, I think it was a condensed metaphysicist the sun. So in that, no matter what he tried to do to the black hole, he could never get the viscosity of the surface fluid to be less than a certain amount, which was proportional to the entropy and that was a pure black hole study and it turned out that when people looked at experiments on the most, on the least viscous fluids, no matter how they manipulated the fluids experimentally, nobody found the fluid, who was that exceeded the bound. With Simon Starinet, who discovered this bound. I just took that as an example, there's nothing particularly special. There were lots and lots of examples like this, this one was easy to explain. There's a nice, simple equation that goes with it and it's so down to earth that it's very easy to understand, not understand where it comes from, why it's true, but what it says. - So, okay. I have two questions and he first one is, I'm not very familiar with this quantum gravity before this lecture, and there's one thing that seems very well to me is that, where is the quantum holograph and does it physically exist? And this is if- - You're asking where the...? - Yeah. - I think the answer is that you take any region, any region whatever, this region here of space, and you want to incur the living room and you want to ask, how the information is encoded? And the answer is that the amount of information you need to describe the interior of this room is never more than the surface area of the boundary of the room and so you can always say, you pick your region and then the answer will be on the boundary of that region. So it's a mathematical statement. What about the universe? Well, the universe does have a horizon. The natural place for the hologram describing the entire universe would be at the cosmic horizon of the universe but that's something that is still being studied.

So the natural thing to say is we take the whole entire observable universe. It's bounded by something called the cosmic horizon and that would be the natural place where you might want to say the hologram was. Now I'm not sure that all my colleagues agree with that and that's still something that I think is work in progress. - Okay, and the second one is radicaly and is related to a former question. How do you define two points our nearby, as we discussed that, you cannot travel at a speed, greater than the speed of light between two nearby points? And to what extent does these two points can be considered as nearby as you stated? - Okay. Send messages back and forth in small amount of time, you'll say they're nearby. I'm not sure what else to say. I don't know, Raphael when said two points are nearby? - Yeah. - Hi, thank you for the lecture. So the famous quote unquote historical dilemma is that the Copenhagen interpretation of quantum mechanics is not irreversible while the shortener equation is very much times symmetric. Do you believe that these deeper insights into the workings of quantum mechanics and as they relate to general relativity, as you laid out in the lecture will deepen our understanding of our interpretation of the wave function, or even perhaps change or offer a new interpretation of the wave function? - I'm only gonna say that. That's a wonderful question. I think that is a really, really good question, is all of, I've always felt that the puzzles of quantum mechanics, the many world's interpretation, all the very, very confusing things about quantum mechanics, would only eventually get solved, when we understand the connection with gravity. I still think that, but I don't. If I knew how to do it, how to make those connections, I would've published them. No. I mean, my feeling is that the answer to your question is understanding these aspects of quantum gravity will tell you more about the inner working of quantum mechanics, but nobody has really, actually, that's not been a primary concern of the people doing this kind of work.

They tend to be a very focused, pragmatic people, if you can call a theoretical physicist pragmatic, who will tend to solve problems that can be solved. This is part of the art of being a good theoretical physicist is to identify those problems, which are hard enough that the results of them of a solution will matter and be important, but were not so hard that we'll just sit around for a hundred years, scratching our butts over them. And so this general feeling of my friends and so forth, and I sort of share it, is that these problems of the foundations of quantum mechanics are real problems but boy, they've been around a long time. People have struggled with them. People have not been able to make any real sense out of it. It's not even clear they're real refinement said about it. He said the problems are so confusing that he can't even tell if there's a real problem, and that is the way it feels. it's like thinking about consciousness or, so the pragmatic side of physicists tends to make them steer away from problems like that. Will they come back to it, perhaps? But at the present time, I think all of this has not impacted the most fundamental understanding of quantum mechanics, which is disappointing in a way. - Okay, we have time for two more questions, i think one at the frontier? - Yes, I also have a question about, we talked before about collapsing instead of entangled particles into a wormhole at, one here and one at Alpha Centuari. And I wanted to ask, if that in turn also means that if we have a wormhole and it the case that we also get back a set of entangled particles? - I am still having a little trouble hearing. Can anybody repeat it? Some voices and it's nothing special. Some voices I simply have difficulty. There's a certain range of frequencies.

Yeah, absolutely. Yeah. For example, you have these two entangled black holes, which form the wormhole. What happens if those two black holes evaporate? They each just get transformed into radiation particles that go out, but those particles will be entangled. So that's exactly right. - Got one last question just here. - Now the last question 'cause I'm beginning to fade. - Yeah. Try now. Okay, I'll say that again. I'll ask a much simpler question than I was planning to. You mentioned that there's a definition of the layoff exponent that has to do with quantum gravity. I was just wondering if you could say more about what system that exponent is referring to and where that definition comes from? - Well, it's a wide variety of systems, but any system, the most well understood case I would say is this S Y K model, which is also a theory of strange metals. The napping exponent has to do with exponential growth. When anything grows exponentially, it varies like E to some constant times, time that constant in this context is called the napping of exponent. What is it that's growing? Well, the simplest way to say it is, it's the growth of the region of influence of the perturbation. In other words, this growth of what I called size earlier. What did you ask me again? I forgot. - What system is referring to? - What system is it referring to? Any kind, pretty much any kind of quantum chaotic system. But as I said, the best understood one at this point is this S Y K theory of strange metals, which is also a theory of extreme or near extreme black holes ,S Y K that's the initials. Sachdev-Ye-Kitaev. So if you, that's where most of it has been worked out in the greatest detail. I think the only way that people would be left unsatisfied is only, and so far as they're hungry for more

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