

In our Time Programme 62
Relativity and Quantum Mechanics

Melvyn Bragg : Hello, Einstein left us with his theory of General Relativity, which explained how gravity works on the scale of stars, galaxies and the universe itself, and Schrödinger left us with the equation that explained the mechanics of the tiny quantum realm. Both theories worked to wonderful effect in their own worlds, but and this is the sticking point, gravity is strangely absent from the quantum realm and planets behave nothing like particles. The enigma for scientists throughout most of the last century is that, as they are currently formulated General Relativity and Quantum Mechanics cannot both be right. The history of 20th century physics has been a struggle to find a way to unite them, to find what has become the holy grail of modern physics the Grand Unified Theory.

With me to discuss the dilemma of modern physics, and the quest for its solution is Brian Green, Professor of Mathematics and Physics at Columbia University, and author of "The Elegant Universe: Superstrings, Hidden Dimensions and the Quest for the Ultimate Theory". I'm also joined by the Astronomer Royal, Professor Sir Martin Rees, whose work "Just Six Numbers" also tackles this problem.

Brian Green can you explain ...can we begin by explaining why Einstein's theory of General Relativity can't be incorporated into the current understanding of Quantum Mechanics?

Brian Green : Sure. The basic idea in Einstein's theory of gravity and general relativity, strangely enough is that the fabric of space itself is connected with the force of gravity. It's kind of a hard idea to imagine, but it's as though the fabric of space bends and warps, and in that way communicates gravity, the only thing we need to know though, is that the curves in space from his theory are viewed as gentle, gentle curving geometry, but at the other end of the spectrum, in the quantum realm, we learn that microscopically the universe is a jittery, frenzied turbulent arena, very different from the gentleness of Einstein's theory, and it's that jitteriness of Quantum Theory versus the gentleness of General Relativity, which makes it so hard to unite them together.

Melvyn Bragg : In your first sentence you said, "the fabric of the universe", could you tell people what you mean by "the fabric of the universe", I don't know.

Brian Green : Sure it's one of the more elusive ideas of modern physics, but it's a very powerful one. It's as if we all immersed within an environment, the fabric of space, it's the stuff around us, you can't really grab it or hold onto it, but you can feel it, because right now, each of us is being pulled by gravity, we feel that, each one of us, and according to Einstein it's warps in the fabric of space which cause us to feel gravity. So you, me, everybody else right now, we are sliding down an indentation in the fabric of space cause by the presence of the Earth, we are all moving in a sense under that force right now.

Melvyn Bragg : And why is that so distinctive from Quantum Mechanics? Why is that relationship so far away from the way in which you understand the world at the tiniest level? One would presume that from the tiniest comes the greatest, from the small comes the big, from the detailed comes the general, and so on. But what you're saying, I mean my goodness am I being banal...? Nevermind...here we go, what you're saying is right there's this huge theory which gently warps the fabric of the universe, and then....but it is built on the particles, the quarks (see <http://members.xoom.com/Templarser/quark.html>), at the bottom, which...a theory which has got nothing to do with the huge theory and so ordinary Joe's would say, "Why don't the building blocks lead to the building?"

Brian Green : Well that's exactly what's been motivating us for 50 years, we hold that same intuition that the big stuff should be built up from the small stuff, and therefore the two theories that have been developed of the small stuff-Quantum Theory and the big stuff-General Relativity, should fit together.

They should smoothly move from one to the other, but as they are currently formulated they don't do that. That's been the driving force. Now why don't they fit together? Well we think it's because, when you formulate Quantum Theory, it's a very different language, it's a very different philosophical orientation, to how the universe is put together, and that has been part of what we'd need to overcome in stitching these two theories together.

Melvyn Bragg : But when we talk about "missing physics", we mean we've got the little, we've got the big, we need something in between to link them together...

Brian Green : We need a bridge, between them.

Melvyn Bragg : Yes. Martin Reece, how do you see that?

Martin Reece : Well we do need the bridge, but we've got on fairly well in most of science without the bridge, and the reason for that is that normally we don't have to worry about Quantum Theory, that's the micro physics and gravity at the same time. In the case of ordinary atoms and molecules, we have to worry about all the **counter intuitive** effects that we've learnt about since the 1920s, called Quantum Theory, but on the scale of single atoms, gravity's quite unimportant. On the other hand when we get to the astronomical realm, the Earth planets, stars etc gravity is the dominant force, it's what's holding us down on the Earth, but in large objects like planets gravity is dominant and the counter intuitive features of the micro world, the fact that on the very small scale we can't localise things, we have this intrinsic uncertainty, those effects are not as important on something as big as a planet, and therefore it's only in extreme situations that we actually need to confront this unification and those extreme situations come first of all right at the beginning of the universe, when we believe everything in the universe was squeezed to the size of an atom as it were, so we clearly have to worry then about gravity, and so we won't understand the real beginning of the universe until we have a theory that can cope with both gravity and quantum theory, and also there are other exotic situations and of course as Brian Green said, we won't understand really what space is like unless we can understand its structure and why it has the effect of transmitting gravitational forces, as it were.

Melvyn Bragg : Don't you find it intellectually annoying though, to put it at its very slightest, that these two things can't be connected? I mean in your work, you find yourself able to do your work without any reference for one theory, without any reference at all to the other, you don't think that perhaps the other might be having some effect that you haven't, dare one say it, imagined or thought....?

Martin Reece : Well certainly we'll get a deeper insight when we have this complete theory, but I think it's important to realise that most of science gets along on the basis of its set of concepts that don't involve all these deep mysteries. Ordinary atomic physics and chemistry and certainly biology, proceed independent of all this. So it's only some kinds of science which actually depend on having these new theories, but conceptually of course, these theories are crucially important, because in a sense, they would be the next step in the quest to understand the basic stuff the world is made of, that goes back to the Greeks. We have understood for at least this century, that everything is made of atoms. We now understand the structure inside those atoms, but the next step of course, is to try and unify all the forces to connect the forces that govern the micro world of atoms, these are the forces of electricity, the forces that hold atomic nuclei together, which we do understand to some extent, and to link those with the force of gravity, which is what we feel here on Earth, and that is the challenge which Brian Green is addressing.

Melvyn Bragg : I'm coming back to Brian Green in one moment, but as I understand it, Heisenberg's Uncertainty Principle is one of the most profound aspects of Quantum Mechanics. Now can you just say how it affects Quantum Mechanics and why it has no place in the work you're doing in astronomy?

Martin Reece : Oh it has a very big place in my world, because the whole nature of atoms depends crucially on the fact that atoms don't obey the ordinary billiard ball equations that Newton taught us, and to understand everything about atoms, and how they stick together to make molecules, planets and stars, we certainly need to incorporate Quantum Theory, and indeed most of 20th century science and technology depends on the fact that on the scale of atoms everything behaves in this very spooky way, as it were, where you can't say simultaneously exactly where an electron is and exactly how it's moving.

Melvyn Bragg : I expressed myself badly because what I meant to say was that what we know about that, does that affect your work on positioning the planets for instance?

Martin Reece : Well when we are talking about the gross features of the universe, the planets and the stars etcetera, then we are concerned with gravity, and Einstein's theory of gravity, is good enough for all these situations. The planets and the stars move in their courses, through space according to the laws of Einstein's theory, which in fact in these contexts aren't too different from what Newton taught us 300 years ago,

and because the planets are so big, the sort of jitter or fuzziness in their positions, which stems from the Heisenberg Uncertainty Principle is trivially small, because the bigger an object is the more firmly localised it is. So it's only when you get down to the very small, that you have to worry about this fuzziness, or in the case of the universe, when you get back to the incredibly high densities which prevailed at the beginning when the entire universe as it were, was squeezed so small that a quantum fluctuation could shake the whole thing.

Melvyn Bragg : So we've reiterated what you said at the beginning that you can effectively get on with the work you're doing with one theory, and without the other. Brian Green, more than once Martin Reece has pointed us towards the big bang which.... as being both massive and tiny, supposedly they tell us containing all matter in the universe yet compressed into something incredibly small. Is it calculations in this field that are the driving force behind the quest for the Grand Unified Theory?

Brian Green : Certainly. The deepest questions that a unified theory such as String Theory faces is trying to describe extreme realms of the universe where you need both the laws of gravity and the laws of Quantum Theory, and those are realms that are huge and heavy, but also tiny from the point of view of size, so the big bang when everything in the universe was crushed together to incredibly small size, it's heavy but it's small. Black holes; another realm where a lot of material is crushed to incredibly small size, again it's very massive but very tiny. Those are the realms where these unified theories come into play, because you need the ideas of both Quantum Theory and gravity, namely General Relativity.

Melvyn Bragg : So what do you know about the big bang in terms of that would make sense to me and I hope to the people listening, that gives you hope that these two theories will come together. You've described in general terms, what more particularly?

Brian Green : Well the big bang is an area of very active research today, and String Theory by no means has resolved many of the puzzles surrounding the big bang. But black holes, the other example I gave perhaps better illustrates some of the power of these ideas. Because in the last few years, String Theory has been able to resolve an idea that was initially put forward by Stephen Hawking in the 1970s, having to do with black holes. He discovered an interesting fact, black holes it turns out embody a certain amount of disorder, or the more technical term is "entropy". But nobody could figure out where the disorder in a black hole came from. Finally String Theory using the new ideas of the last few years has been able to very accurately describe where the disorder in a black hole is and came out with a numerical answer that agrees exactly with what Stephen Hawking had predicted. So it's a very powerful confirmation that these ideas are making contact with real physics.

Melvyn Bragg : Could you tell us...? Is it possible, to tell us, I mean some things aren't possible to say in a conversation, but is it possible to tell us what String Theory is?

Brian Green : Sure, I think the basic idea of String Theory can be described quickly in a nutshell, as Martin Reece was saying. We have for thousands of years asked a simple question: "What is the stuff of the universe made of?" - namely if you take any piece of material: wood, iron, anything, slice it in half, slice that piece in half again and keep on cutting, what's the smallest ingredient that you'll come upon, and indeed in our century we've learned about atoms, but we know atoms are not the end of the line, because they are made of smaller things, they can be split they have little electrons that swarm around a central nucleus, and it can be split because the nucleus itself has neutrons and protons, and they're not the end of the line either, it's somewhat like a sequence of Russian Dolls, inside neutrons and protons are smaller particles. Discovered in the late 60s, known as "quarks". What String Theory does, it comes along and says there's one more layer of structure, deep inside an electron, deep inside a quark, deep inside any particle in fact is a little tiny loop of energy, it's a little filament of energy, vibrating to and fro, and the key idea is that just like the string on a cello or a violin can vibrate in different patterns which our ears sense as different musical notes, the little strings in String Theory, also can vibrate in different patterns, but we don't hear them as different notes, rather we see them as the different particles in the world around us. So using the metaphor an electron is a string vibrating like A sharp or a quark is like a string vibrating as a C flat or something of that sort. So that is the way in which, we can think of all the rich material in the world around us, being generated from one fundamental vibrating ingredient.

Melvyn Bragg : How do you see, know, understand, how do you get your...? I mean I'm..... hands on that one vital ingredient...can you see it? Or is it just....is it an imaginary...an act of imagination?

Brian Green : At the moment it's an act of theorising, so it's imagination but bolstered by the quantitative ideas that we're able to develop surrounding the idea.

But the reason we can't see it yet, is because the strings are really tiny, so just to give you a sense, their about well numerically a billionth of a billionth of the size of an atom, so they're tiny but an analogy I think gets the idea across better. If you were to take say a single atom and magnify it to be as big as the entire known universe then the little string in String Theory would magnify roughly to the size of an average building of maybe ten stories. So a ten story building is to the entire universe as a little string is to an atom. So that's why they're so difficult to see directly, because it's way beyond our technology to see something that small.

Melvyn Bragg : But you're absolutely sure they're there are you?! (Mel giggles)

Brian Green : Absolutely sure? Certainly not. We won't be absolutely certain until there's experimental proof of these ideas. But the last 10-15 years have convinced us that this theory can solve problems that could not be addressed in any other method, and just going back to the somewhat philosophical side, I think each of us, I think has a gut sense that the universe cannot really be described by a patchwork of two good theories each of which is incompatible with the other. The universe exists, it's a single place so it should be a single consistent theory describing it all, and that's really what's driven us to try to construct that unified theory.

Melvyn Bragg : Martin Reece, Einstein tried to solve this puzzle didn't he? Why did he not succeed?

Martin Reece : Well Einstein was really trying to do it prematurely, he didn't know enough about all the forces that need to be incorporated, so his efforts were doomed to failure, but he, obviously was striving for what Brian Green's colleagues are still striving for, and I think the interesting question is "What are the prospects of succeeding?". Because first of all, as Brian Green said, the scale of these strings is far far smaller than we can directly measure, and also they involved very, very complicated geometry, not just three dimensions, but 10 or 11 dimensions, and so first of all they involve mathematics which for the first time is challenging mathematicians. I mean Einstein used maths that was on the shelf already from the 19th century, so did the pioneers of Quantum Theory, but the mathematics need for Superstring Theory is still challenging mathematicians who have got to learn more mathematics. It's the first time in science we've needed more mathematics to make a scientific breakthrough, but the other point is.....

Melvyn Bragg : Really, the first time ever?

Martin Reece : Well, maybe not quite the first time, but if we think of the great advances in science they've normally used maths to pukka mathematicians is fairly old fashioned and standard, whereas that's certainly not the case for what they're thinking about in superstrings. But the other issue, really, how will we test it's right? Because we can't directly probe these strings. We will hope that one can understand well enough the theory that you can actually calculate something about ordinary atoms, ordinary electrons etcetera and the ordinary forces, which we can perhaps test, and just to highlight the limitations of present knowledge of the microworld we know they are atoms and electrons, etcetera, we know about different forces, but we don't know why they have those particular strengths, we don't know why an electron weighs 1800 times less than a proton, and things like that, and if this Superstring Theory succeeded in explaining some numbers that we can't yet predict, then of course it would gain credibility, so we don't actually have to observe this tiny scale, we need to be able to calculate from it something we can directly observe, so that it gives a number which we can compare with observation, and then there's another thing which interests me very much in a more philosophical way, and this relates to my book "Just Six Numbers", which addresses the apparent special nature of the laws in our universe, and the question there, I would like to know what Brian Green thinks about this, is whether this ultimate theory will lead to a unique set of laws of nature, in our low energy world, or could it be that a big bang cooled down and ended up with a quite different physics, different numbers of dimensions, different kinds of atoms in it etcetera, because if that's the case, it will mean that we can think of our universe in a different context and in a sense cosmology would become rather like biology, in the sense that we won't be able to explain directly the physics we see, because some sort of historical accident of how our particular big bang behaved, and so I think it's very interesting to know whether we will ever have this theory worked out enough, whether our brains can cope with the mathematics and also what consequences it will have.

Brian Green : Well I hope that String Theory ultimately will give a unique prediction for how our universe is and that prediction actually agrees with what we see in the world around us, because as you say, there are a bunch of numbers that people have measured fastidiously over many years, some of which you've mentioned, the mass of the electron, the mass of quarks, the strengths of the forces and so forth, but nobody can explain the numbers that the experimenters get, and it's not just a question of idle philosophising, because it runs out that if those numbers had been even a little bit different, a few percent different, the universe as we know it would not exist, it would go away.

Stars, for instance, rely on nuclear processes, which themselves require delicate interrelations between these numbers, these particle masses and so forth, and if you change those numbers the nuclear processes go away, stars don't light up, and without stars the universe is just a very different place. So I think perhaps the deepest question that science faces is "Why is that those numbers have just the right values to allow stars to exist and planets to form, and at least on one planet life to actually exist?".

So we hope that String Theory will come to a unique answer but we don't know as yet. We don't know enough about the theory to know if it will do that.

Martin Reece : Yes.

Melvyn Bragg : In passing, Martin mentioned working in more than 3 dimensions, Einstein suggested time as a 4th dimension, but you're up to 9, 10, 11 dimensions. I just cannot....I mean I 've got no purchase on that. Can you try to give us some idea of what you are talking about there?

Brian Green : Sure. One remarkable feature of String Theory is that it only seems to make sense, internal consistency of the theory seems to demand that the universe have at least 6, and probably 7 more space dimensions than we are directly aware of, so first of all what does that mean. Well we all live in a universe where we freely move through 3 dimensions all the time, left-right, back-forth, up-down . Three independent directions, include time as you mentioned that takes you to 4.

We're saying there are 6 more, probably 7 more space dimensions beyond the one's that we know about. How do you think of that? Well, I think an analogy helps to get the idea across. If you imagine in your mind's eye, say a big long piece of a garden hose that you stretch out between two posts and a field, and you walk maybe half a mile away from that garden hose, and you look back on it, well it's going to look like a one dimensional line, because you can't actually see the thickness of the garden hose, from a distant vantage point. So if a little ant were living it's life on the hose, you'd say, "Well it can move in the left-right dimension, but that's it. Only one direction in which it can move, on the surface of the hose. But then if you take a pair of binoculars for example, you zoom in on the garden hose, you now see that it has thickness, you now see in fact there's a second dimension, a dimension that's curled around the surface of the garden hose. So the little ant can not only walk in the left-right direction, it can also move counter clockwise or clockwise, a new direction that you only know about, if you can zoom in and really magnify the object that you're looking at. Well we think the universe maybe very similar to that..

There are three big obvious space dimensions, like the unfurled extent of the garden hose, but there maybe others, perhaps 7 more curled up dimensions, like the circular girth of the garden hose, but we think that perhaps they're so tiny, that as yet, nobody has the equipment necessary to magnify them to a scale that we can actually see, and that's how we make sense of this rather strange, prediction that there are more dimensions than meet the eye.

Melvyn Bragg : Why do you choose 7 and why are they significant?

Brian Green : Well, when you study the mathematics of String Theory, it turns out that there are equations that demand that particular number. Basically there's roughly an equation that says "Unless there's 7 more dimensions this theory falls apart". So we pick that number in order that the theory makes sense, and then we go forward and see what else it has to say about the universe.

Melvyn Bragg : Is this entirely speculative, imaginative? I mean what empirical evidence is being brought to bear on this at all? Is this just mathematicians having fun ? Is this angels dancing on the head of a needle?

Brian Green : I don't think so, I don't think it's angels dancing on the head of a pin, because we do believe that

General Relativity describes gravity, because experiments have shown it. We do believe that Quantum Mechanics describes the microscopic realm, because experiments have shown that. We also feel that there should be one theory that puts them together in a consistent package, and String Theory is a theory which does that. So there is experimental support for the two underlying structures of the theory, and then we have to see what that union, that consistent union tells us, and one strange fact is it seems it tells us that there are more dimensions. Let me just add to that, there is an experiment that's going to be carried out in the next couple of years, in the US, at Stanford University and in Colorado, where experimenters are going to try to search for signatures of the extra dimensions by very, very accurate measurements of gravity on tiny sub millimetre scales. So it's a long shot experiment, but it's possible that, with those experiments they will get indirect evidence for the existence of these extra dimensions, and if those experiments are positive, I think it's going to be one of the most dramatic discoveries of all time.

Melvyn Bragg : Why? Martin Reece, why do you think that will be one of the most dramatic discoveries of all time?

Martin Reece : Well it'll certainly, if it works, be telling us something new about the fundamental nature of space and time, and being at least a step towards unification, it will indicate that Brian Green's theory is on the right lines, and of course, that will increase the chance that we will one day, this century perhaps, have this theory that will explain the basic forces of nature. But I think it's very important, for physicists when they talk about this to emphasise that this is just one branch of physics, and physics is just one science, and I think we have to be modest and realise that for most of the rest of science, this theory is going to be entirely irrelevant, and let me give an analogy here. My favourite analogy is with a game of chess. If you imagine watching people playing chess, then eventually you could figure out what the rules were, but of course what makes chess interesting, is not the rules, but the enormous complications that they allow in the play, and what we are doing in physics, is to try to understand the basic rules that govern nature. But just as in chess, simple rules 64 squares on the board, 6 types of pieces allows immense complication, so when we've got these rules playing out in our vast cosmos, then of course what they allow is all the complexity of the everyday world and the astronomical world and all the complexity, and so it is that which is the unending quest for science, and another way to put this is that in the case of science, we can highlight the frontiers, the very big, the very small, and the very complicated.

What we're trying to do is to unify the very big and the very small, that's what Superstring theory may do, but the greatest frontier of all, which most of science is concerned with is the very complicated and that is, the unending challenge of science.

Melvyn Bragg : And you don't think String Theory will necessarily address that?

Martin Reece : Well I think it won't be relevant to that because if you're a biologist, or a chemist, you don't really care about what's happening inside an atom, and you care still less about what's happening on scales a billion billion times smaller than an atom, and so it deepens our insight, it's of great philosophical importance, to all of science but, I think Brian Green would agree, that to the practitioners of most sciences, it's of philosophical interest, but it doesn't affect the work they do, because we can't actually do a calculation from this level for a single atom. Certainly not for anything complicated.

Melvyn Bragg : But to come back to where we started, Brian Green, the Grand Unified Theory, the theory of everything, there's an expectation in those very phrases, that it'll be "Shazam Boom", all will be solved and the big bang will be solved and by having a theory of everything, by uniting these two theories, we will know in a fundamental way which will permeate everything else that we know....

Martin Reece : It's an unfortunate name in my opinion.

Melvyn Bragg : ...well, but do you think that that's so.

Brian Green : Well I think that as we discussed before, that string theory may well one day give us an explanation for the big bang, how the universe began, and how it evolved from its state way back then, maybe 15 billion years ago, to the form we witness on a dark starry night. But it's certainly the case as well, that we are limited in our ability to go from the fundamental rules as Martin Reece was saying, to understand the most complex things around us. The brain for instance, psychology, I don't think anyone's going to understand depression, from the point of view

of String Theory, but we *will* understand other more simple questions, such as, how the universe began, how a black hole exists, what it's like to be at the centre of a black hole. Those it turns out are far simpler questions than understanding a question like depression. because we're talking about the fundamental structure of our universe, and that I think is a compelling kind of question to try to address.

Melvyn Bragg : Mind you, I mean...I'm treading very, very carefully here with you two, but it is as....been proved true again and again over the last few hundred years that you don't know what the outcome of these discoveries are, I mean Newton's laws of motion led to things that he could not have imagined, and so on.

Brian Green : Yes, absolutely, one always has to bear in mind that discoveries which seem abstract and esoteric today, can sometimes have important implications for things in the future, so could well be the case with String Theory as well.

Melvyn Bragg : Thankyou very much Brian Green, excellent book, "The Elegant Universe", Martin Reece excellent book, "Just Six Numbers", and thankyou very much for listening.