Mike Biercuk – 'Realising the Quantum Dream'

Moderator: Welcome to the podcast series of *Raising the Bar Sydney*. *Raising the Bar* in 2016 saw 20 University of Sydney academics take their research out of the lecture theatre and into 20 bars across Sydney, all on one night.

In this podcast, you will hear Michael Biercuk's talk, *Realising the Quantum Dream*. Enjoy the talk.

Mike Biercuk: So thank you all for coming. It's really nice to be here and to have the opportunity to chat with you a little bit about some of the work that we do and the direction that our field is moving, because it really is an exciting time. But before I get into that, I did want to raise a glass to everybody, to thank you, but also, honestly, to give thanks. You know, whether you think so or not, I think we're very fortunate that we get to sit in a bar and talk quantum physics. A lot of people around the world are not able to do anything remotely like that. And so cheers to all of you, thanks for coming and I hope you enjoy the story I'll tell you over the next half hour.

And the story is based on the vision that was put forth by a gentleman named Richard Feynman. So Feynman – if you have not heard of him before – was a great leader of the development of a whole range of fields in modern physics. He won the Nobel Prize in 1965. He was one of the fathers of the atomic bomb. He was deeply involved in the Manhattan Project.

But one of the things that he did that was really inspirational to people like me and, and to a whole generation of researchers, was put forth a vision that talked about a new kind of level of technological superiority, that humans could achieve over nature, by taking complete control over matter at the most fundamental levels. The idea that you could control matter at the level of single atoms, you could manipulate them.

Now obviously he had a lot of experience in subatomic physics. He was involved in splitting the atom associated with nuclear weapons and nuclear energy. But what he envisaged here, was saying that instead of taking a big block of stuff – like steel or whatever – and carving something out of it, let's start from the bottom and let's build our technology up, in something that we now call bottom-up engineering.

This was a true revolution in the way people thought about building technology, not just because it was so different to start from single atoms, but also because what he conceived was that in addition to being able to build up from these fundamental building blocks of matter, you could access new kinds of physics that you wouldn't otherwise be able to access. And in particular, what he envisioned was taking control of light and matter and taking over the quantum physics that you encounter when you get to that level.

So what is quantum physics? Quantum physics you've probably heard about, at least in the popular press. It's a branch of physics that deals with very small things. It deals with fundamental particles of matter, like atoms or electrons, and fundamental particles of light. These are called photons. That's an extremely loud bus. So with the ability to access these very small things, you gain the ability to peer into matter and exploit the new things that you find.

Quantum physics is not just about the things that are small. It's really about a different way of understanding nature. It's about understanding what happens when the rules that we're familiar with, the things that govern astronomical bodies or … oh thanks, that's awesome … or rockets or the trajectory of a cricket ball, when those rules break and instead we have to replace them with something really different. That's what quantum physics or quantum mechanics is.

But it's not just kind of esoterica; quantum physics is probably the most successful physical theory ever developed. And I mean that in a very specific way. What I mean is that it gives us the ability to predict how things will behave. This is kind of the test that we have for how useful a theory is. Quantum physics gives us predictive power. It allows us to kind of estimate how something will be behave. We say, "Oh, we have an electron. This is how we think it will behave," and it turns out that quantum mechanics correctly gives us insights into that behaviour.

Well that's really useful if you want to do something leveraging that physics. And whether or not you know it, every one of us is kind of living our lives governed by the rules of quantum physics. Now I don't mean this in a kind of silly, spiritual way; I mean in terms of our technology. I mean every one of us you has probably been on your mobile phone today. Maybe some of you caught an uber car. Maybe some of you are really bored to tears and you're reading the news. Every, every time you're interacting with a mobile device or your laptop of communicating via the internet, you are using technology that's based on our understanding of quantum physics.

Quantum physics has given us the information age. Everything that you encounter works because of our understanding of quantum physics. For instance, microprocessors: The computer chips that power you mobile phone, your laptop, internet servers, they all work because of our understanding of a kind of material called semiconductors. Semiconductors are materials that can behave like metals; they can conduct electricity. Or they can behave like insulators and not conduct electricity, just depending on a signal that you apply to it. That's how we build switches. If you have switches you can make computer logic, Boolean logic.

All of that works because of our understanding of quantum physics. It's really quite a remarkable thing. It's extremely powerful. It's also given us global positioning system. If you took either uber or checked in with a location-based service, you were relying on atomic clocks, clocks that get the ability to keep a very precise tick based on quantum physics. Quantum physics governs absolutely everything you do. It really is remarkable.

But despite how ubiquitous it is, how successful this physical theory is in having delivered what today totally governs our society and our economy, what's really pretty remarkable and what inspires me and relates to, to Feynman, is that we really are only leveraging the most simple phenomena in quantum mechanics. It's kind of the, the, the absolute cream in terms of the simplest stuff that's risen to the top that we can access.

The way to think about this is that we're building our technology using what I'll call bulk properties. We have a big piece of material like a semiconductor, like silicon, the famous one that we use in most of our technology. And if you take enough particles, like electrons, charge carriers that obey the rules of quantum physics and you match them together, you can talk about the average properties. How do they all behave together?

It’s a little bit like thinking about a giant pile of sand. You can understand how tall the pile of sand will be; you can look at it and say, “Well it’s kind of brown,” or, “It’s kind of white,” depending what beach you’re on. You can even do remarkable things like make astounding sand sculptures, right? If you’ve ever seen some of these competitions, people do amazing things, leveraging our understanding of the bulk properties of sand: how tall can you make it, how can you make it stick together?

But there’s a completely different paradigm, which is to instead say, “Let’s not look at the bulk; let’s look at what happens if you go down to the individual grains of sand.” And if you’ve ever seen a picture of individual grains of sand, you’ll know that there’s a huge amount of complexity. Some of them are parts of seashells; some of them are little, tiny crystals. But all of that is missed when you just look at the giant pile of sand.

That analogy carries over to the way we use quantum physics today, that we’re only using these bulk properties, these average properties. And the exiting question is: What happens if instead of doing that, we can go and look at the individual grains of sand, which for our purposes are going to be individual atoms, or other individual quantum systems like electrons or single particles of light that we call photons?

In addition to the technological part that I told you about, there really are some interesting things buried in the theory. There are properties that maybe you’ve heard of. One that we talk about in the, in the vernacular is wave particle duality, that you can’t just talk about an atom or an electron being light a little ball. Instead it’s something that spreads out in space, more like a wave.

There are other things like entanglement, which says that quantum mechanical systems can be coupled together and can share a link, no matter how far apart they’re separated. You can separate them over the distance of the universe and, as far as we understand, they maintain this quantum mechanical link in a way that’s totally different than any other form of classical communication that we know about.

All these things are kind of interesting parts of the theory. It’s interesting parts of the mathematics and the kind of physical description of the world. And they’re completely dissimilar from our daily experience. You are not entangled with anything else. You are here or there; you’re not in both at the same time, which is a way that in our common language we describe these exotic effects in quantum physics.

A particle can be in two places at once in quantum physics. And it doesn’t choose one or the other until you observe it. It sounds insane because it’s so different from our daily experience. It raises all sorts of really interesting questions. It challenges us to interpret nature on these tiny size scales. We struggle because we always anthropomorphise everything, right? We say, “Well an atom must have an experience like we have an experience. It can either be here or there.” But that’s just not the way the world works. It’s actually quite different than that. It can be both at the same time, until you look.

But that of course raises huge philosophical questions: Why is that the way the universe is? Why is that reality? These are really hard questions and they bring all sorts of really interesting and exciting things. You may have heard in the news the last couple of days; there was discussion about this thing called simulation theory. And we’re all living in the matrix, right, that it’s all a big computer simulation. First thing to say is, “That’s bullshit.”

But it's a part of a long history of people thinking that the most advanced piece of technology we have is the model for the universe, but it does in fact link to something in quantum physics, this idea that you have a particle that can be in one place or the other, and it's actually both at the same time, and it doesn't choose one or the other until you measure it.

That brings us to something called many worlds theory, that in fact every time you do a measurement, every time you observe your particle, you choose one outcome and you create a new universe, right? It's kind of difficult to comprehend and it raises these huge philosophical questions about the way the world is, the nature of reality, meaning of life. But in a technological perspective, that stuff is just completely glossed over and it's completely absent from the technologies that are in your mobile phone, right? Your mobile phone is not in a quantum superposition. It's not entangled.

These are things that, for many decades, people would deride and great scientific minds went to tremendous lengths to try and show why it had to be wrong. Einstein called entanglement spooky action at a distance, because he thought it was nonsense. And people went to great lengths, coming up with all sorts of theoretical questions to demonstrate why these properties had to be wrong.

Well for the last 60 or 70 or 80 years, people simply ignored them. And what Feynman did was say, "Well maybe we shouldn't. Maybe instead of ignoring them and building our technology without any of this, we should think about what would happen if we could control technology and gain access to all of that weird stuff." When Feynman proposed building technology from the bottom-up in this famous talk called *There's Plenty of Room at the Bottom*, he was conceiving building technology that leveraged all of this physics, which is really exciting. This was Feynman's dream.

What's exciting to a young scientist … well, I'll use that loosely. I used to think I was a young scientist, but now, not so much. When I was a young scientist, I was inspired by the fact that only in the last few decades, did we learn that all of these phenomena – wave particle duality, superposition, entanglement – they're all real. They're not just strange maths. And they are things that we can measure in laboratories, laboratories like mine, like those of my colleagues around the world. This is not just strange math. This stuff is real.

And so all of a sudden, Feynman's vision of accessing this weird physics is within reach. And in 2012, the Nobel Prize was awarded to another scientist, another pair of scientists, named Dave Wineland and Serge Haroche. Dave Wineland was my former boss when I worked at NIST in the US. And there were citations that it was for measuring ... developing techniques for measuring and manipulating individual quantum systems. What these two great scientific leaders did was develop techniques that allowed us to access individual quantum systems, to verify that all these weird things that we thought were just part of the math, are real, and to allow us to start to build technology using those systems. And the system that Dave worked on and that I work on is based on trapping individual atoms, single atoms. We can kind of confine them in an electromagnetic bottle.

Now we have a technological focus to our work that I'll talk only a little bit about. Feel free to ask me at the end if you want. There are a number of things that have been extremely motivational in our field, saying that if you can access these quantum systems, you can do really crazy shit, right?

You can build computers that work in a way that's fundamentally different than any other computer that we have today; not just more powerful, but totally different. Computers that can solve problems no conceivable super computer you could ever build would be able to solve. New techniques to encode and transmit information with what's called provable security, and new kinds of clocks and sensors that can power all the other things that we use today.

Remember, I told you that global positioning systems work because of these very precise time-keeping instruments that function because of quantum physics? Well we're all working to make ever more precise clocks, powered by these strange rules of quantum physics. And while that sounds like the kind of thing that, you know, only a scientist could love, it turns out like this is exactly what makes secure online transactions work; it's what makes global positioning systems, all these concepts and network synchronisation, that's what makes our economy work. And so it's exciting to people in my field to think about how we can leverage these physical effects to try and build ever-improved versions of these.

So let me tell you a little bit about the research that I do, that my team focuses on. So, as I said, we're interested in accessing individual quantum systems, realised as trapped atoms. And, you know, atoms are a good starting point for us because they are … in the simplest terms, they're kind of fundamental building blocks of matter, of all the stuff that we experience in our lives. It's also really nice that … when quantum mechanics was being developed, it was being developed to try and explain the way atoms behaved. People made all sorts of observations on atoms and they were trying to understand why they are the way they are, why do they absorb light in certain colours, why do they emit light in certain colours. And people went to great lengths to try and explain this. Quantum mechanics is part of what emerged from that work.

So because there's this natural link between the development of quantum physics and a study of atoms, it makes sense for us to go back to the kind of beginnings and start with individual atoms as the place that we build our technology, right, where we're trying to leverage this weird physics.

What we do is we can trap individual atoms, one at a time, in a special electromagnetic bottled called an ion trap. We can confine it. We can hold it in space. We can move it around if we want. We can then control and manipulate its quantum mechanical state with things like laser beams and microwaves, microwaves that are similar to the stuff that's emitted by your mobile phone to communicate with the base station, lasers that are actually really similar to the ones in Blu-ray players. In fact, a lot of the physics that I do has been enabled by developments in Blu-ray. People, maybe ten or 15 years ago, would by a Blu-ray player and rip it apart, just to pull the laser out of it, right? This was the only way you could get them, and that's what's enabled us to access certain atoms in the lab.

Well okay, how do you … what is a quantum state and how do you control it? Well the, the picture that many of you may have in mind comes from my least favourite show on television, *The Big Bang Theory*, right, where you think about what happens in the opening credits, right? You get this picture of the ball and then there's stuff whizzing around, right? That's, that's obviously not real, but it's a cartoon representation of quantum mechanics, right? It's an idea that you have this central nucleolus and then you have the electrons that kind of whiz around it. But sometimes they whiz around this way and sometimes they whiz around this way and sometimes they whiz around this way.

Again, that, that idea of the shells, where the electrons can live, that's a cartoon representation of quantum physics. It came to us by understanding that the electrons can't be anywhere; they can be in certain places.

So as silly as that cartoon may be, it actually tells us something, because when we talk about controlling the quantum state of the atoms, the way we do that is by taking the atom and making its electron go from doing this to doing this. That's a change in the quantum state. That's what gives us access to the quantum physics that we want. And we can do that with lasers; we can do it with microwaves. We can take pictures of the atoms, after we have manipulated them, using a camera that's almost the same as the camera on your mobile phone, right? This is all the kind of stuff that we can do in our laboratory.

Now I'm not alone in this. We're part of a global effort that's looking to build a new generation of technology that leverages this level of control. We call it quantum technology, or quantum tech if you're trying to be sexy and sound like you're from Silicon Valley, right? The idea that we can now put these systems to work is what motivates us. And that's where my team's special focus come in … comes in. As I said, you know, I had worked with this guy, Dave Wineland. He's the one who really developed these techniques that allow us to control individual atoms in traps. That's not something that I did.

What my group focussing on is overcoming a real problem that takes us from where we have this quantum system and we can study it and do whatever, and making it do something useful for us. That's, that's where my team sits. And really, we are straddling kind of disciplines of physics and engineering because when we're thinking about building quantum technology, it turns out that the greatest challenge that we all face is that quantum systems are really fragile. They break very easily. In fact, if you let them just kind of sit around, very quickly they interact with the environment, like all the electromagnetic waves bouncing around from your phone or from Wi-Fi and then they get randomised and they turn back into classical systems.

It's kind of like … remember I told you, a quantum system can be here and here at the same time and it doesn't choose one or the other until you look at it, until you observe it? Well the idea is if I make a quantum system like an atom, and I trap, the environment looks at it, and then it's no longer quantum. It's a big challenge. Overcoming this challenge is what motivates almost all of the research that's going on globally in trying to realise quantum technology.

And my team, in particular, takes concepts from a discipline called control engineering, control theory, and looks to turn quantum systems from these little, delicate flowers, into something robust, into something that you can actually put to work and send out in the field. So if you're not familiar with control theory, it is another thing that is kind of always going on in the background. If you drove here maybe on the M1 or something, maybe you put your car in cruise control because you didn't want to get a ticket going over the harbour bridge, right?

Cruise control is control theory. It's saying that you have a system – it's your car – it's moving at some speed and you want to keep it at that speed. If you're going too fast, you've got to slow down. If you're going too slow, you've got to speed up. And you do that by having sensors that measure and then doing what's called feedback. You say, "Oh, I'm only at 68, I should be going 70, I'm going to speed up a little bit." That's control theory. That's what makes aeroplanes fly.

It's what makes all of our technology work. And that's what we're now trying to deploy to build quantum tech, to build quantum technology.

So my team is focussed a lot on how we can use concepts from control theory, adopt them for how different the rules of quantum physics are – like I can't measure my system 'cause if I do, it turns into a classical system; it's no longer quantum – and then use that ability to make them robust against all the stuff that's trying to mess with them.

So overall, the concept that my group focuses on is looking to exploit all the weird stuff that we find in quantum systems as resources to power technology using superposition and entanglement and teleportation and all the other weird things we find that we used to think were just math, very similar to the way that we started building technology that used the flow of electricity as a source of power, right? Think about how much the world has changed since we did that.

As I said, there are a lot of applications that we're thinking about: ultra stable clocks, detectors and sensors, looking to make these computers that can do things that no other classical computer could achieve. But also, looking to apply them for some very specific purposes that are, are again, the kinds of problems that it sounds like only a physicist could love, but are really motivational. I'll tell you about one very briefly.

This is the study of materials. Why do materials behave in certain ways and can we make materials that do things we want? Again, it sounds like it's only weird physics, but just a little bit of historical precedent tells you how important this very specific narrow-sounding problem really is. If you look back to the development of a system called in the ENIAC, this was the world's first digital electronic computer, built at the University of Pennsylvania in the mid 1940's.

The team that build that system … again, the first digital electronic computer, the precursor to all the modern things that you carry around or that you have in your laptop, that system was designed specifically to solve physics problems. It was designed to the problem of artillery shell trajectories for the army. They wanted to calculate where they should aim their gun if they wanted to hit Hitler, right? So solving physics problems has a great precedent of brining all sorts of other things down the line. But the specific physics problem that we have in mind is really tremendously impactful.

An amazing thing about materials and material science is that it's really easy for us to take a piece of material and characterise it and say, "Okay, well it's, it's brown, it's, it's an insulator, I can't flow electricity through it. If I get one side really hot, the other side stays cold, so it's thermally insulating. It's really brittle; if I go like that it will break." It's really easy to do that, but if I tell you to do the opposite, "Give me a material that's, let's say, brittle and transparent and a little bit green and conductive of electricity," it's extremely difficult to come up with an answer to that problem.

One reason is that we don't have tools that allow us to simulate a lot of the physics that's going on, often, because that physics is governed by quantum physics. Quantum systems, quantum physical systems, are notoriously difficult to model on super computers, on classical computers. What we're trying to do is built a special kind of computer called a quantum simulator, where instead of say programming a super computer to try and model some physics associated with materials, instead we're thinking about, "How do we make a model, a scale model, that kind of behaves in the same way as the much more complicated thing we want to study, the material we care about?"

It's a little bit like making a scale model of an aircraft and studying how it behaves inside a wind tunnel. We're building a quantum scale model of a way more complicated system, like a material with billions and billions of electrons, to understand what the physics is that gives us certain properties so we can then try and invert that problem. One area where we're trying to accomplish this is in making materials that allow electricity to flow with no resistance, with no loss, and this obviously has huge impacts, potentially, for the power grid. I don't have time to like really get into this, but please grab me after if you want to, to hear more about it.

But as I said, you know, I'm not, by any stretch of the imagination, the only person working on this. You might be also surprised that there's about a dozen groups, right in Sydney, that focus on related topics in the development of quantum technology. I came here … maybe you can here from my accent I'm not from Australia; I'm from New York. I moved here because of the strength that Australia, and Sydney in particular, have in quantum science and quantum technology. So it's really exciting to come and be part of that community.

And really, to close, I wanted to build on that idea, that I came here to be part of a community that was really pushing hard on bringing these exotic-sounding technologies to reality, achieving things that for many decades we thought were just math, but now turning them into real things that can do totally profound … achieve totally profound computations (28:25) other technological applications.

So when we talk about innovation, this is what my colleagues and I mean. We mean building things that are unlike anything that has ever come before. We mean building technologies that allow us to control or understand the world in ways that no one has ever done before. That's quite a different definition than what gets talked about frequently when we talk about innovation. We talk abound doing things that are pretty much the same was what we did yesterday, but now with a mobile application, right? So the world is totally different because you used to order a pizza by calling, and now you use a mobile app.

So I know that's political, but I want to argue is that we, as a community in Australia, invest huge amounts of effort into really achieving innovation of the scale that will transform the world. And I often hear people talking about, "Oh well, Australia, we're so small, we can't ever do it," you know, "We can't compete, we can't be Silicon Valley." And I, I call bullshit on that, right? We can do exactly the same stuff. The capabilities in Australia to achieve world-changing technological innovation are here. And it, it's not me at all; it's the group of people, the community that exists in this space, really building technologies that look like nothing that's come before. This is the real innovation that exists in Australia, and in Sydney in particular.

And I told you a few minutes ago about ENIAC, this system that was built in 1940 … in '46 and '47, originally designed to calculate artillery shell trajectories, which has totally changed the world, right? Well the truth is, we stand today, kind of at the edge of the same kind of technological change, that building systems that harness and exploit the weird physics of quantum mechanics, will be as profoundly transformational to the way our world works, our society and our economy, as the creation of the first computers, the first electronic computers.

So it's a really exciting time and it's all happening right here. It's happening at the University of Sydney and the University of New South Wales and Macquarie. This is the real innovation that we talk about and that we're excited about.

And I hope that if you find this interesting or exciting or inspirational, that you start helping to change the conversation and informing our politicians that there's actually a lot more going on here than just flogging wine using a mobile app. It's a really exciting time to be doing this kind of science. I hope you've enjoyed hearing a little bit about it and, you know, we'll see what comes next in terms of quantum technology. So thanks very much and I'm happy to answer questions.

Moderator: Thank you for listening to the podcast series of *Raising the Bar Sydney*. If you want to hear more Raising the Bar talks, head to raisingthebarsydney.com.au.

End of Recording.