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Welcome to IFLScience The Big Questions, the podcast where we invite the experts to explore the biggest mysteries of science, with your host, Dr. Alfredo Carpineti.

I: Regular computers affect every aspect of our lives. They have brought forward a revolution in the way we communicate and live, but even the most powerful super-computer has its limits. Scientists and engineers have found a path beyond those limits, thanks to quantum mechanics. By using the crucial theory of the micro world, computation can take a big leap forward, but how does a quantum computer work and how will they change the world? To answer this question, we are joined by Professor Winfried Hensinger, Professor of Quantum Technology at the University of Sussex.

Thank you so much for joining us. Would you like to tell us a little bit about yourself and your work?

R: Thank you for inviting me. So, my name is Winfried Hensinger, I am a professor of Quantum Technologies at the University of Sussex, leading a research group there to build particle trapped ion quantum computers. I am the Director of the Sussex Centre for Quantum Technologies and also with my other 50 percent I am key scientist and chairman of a Quantum Computing company, Universal Quantum, that works on actually building and constructing practical quantum computers with trapped ions.

I: Wonderful, thank you very much. So, I think you are perfect to answer all our burning questions about quantum computers. I think we'll start from the simplest: How does a quantum computer work?

R: So first of all, let me say quantum computers work entirely different to conventional computers and they work because of a very strange theory in physics called quantum physics. Quantum physics is extremely counter-intuitive, weird. Einstein referred to this spooky – it's certainly something that we don't see in our daily life, and one of the things in quantum physics is that things can be in two different places at the same time. So, an electron can go for two slits at the same time and interfere with itself. So, things like that happen in quantum physics and they really spooked and really freaked out physicists and scientists for many many years and actually still do. Maybe twenty years ago physicists tried to think, can we actually change these very strange phenomena in order to built technologies that can change the way we work and live and one of these technologies is a quantum computer that can solve certain problems where even the fastest supercomputer might take billions of years to solve for us. It's really a machine that isn't there to just do your word processing or it isn't there to kind of do things a little bit faster, but it can solve certain problems that would literally be completely unsolvable on even the fastest computer in another five years of development. This is what kind of makes quantum computers a very disruptive technology because it changes everything. Think of it as like Google's search algorithm. Many years ago, we used all sorts of search engines and then

Google developed a search algorithm and people just went for the search engine because it was so much more powerful than everything else. This is maybe a good explanation.

I: Absolutely. The technology, as you described it is disruptive, is going to push on things that we can't normally do with computers or even supercomputers. Is that why we need quantum computers? Is it because what could potentially harm us is way beyond what our standard approach can deliver?

R: I guess our standard approach is very capable and useful for certain things. So, for example, for your word processing, for many applications, to give you tickets at the train station, standard computers are perfectly fine, but one of the things which is very important for you to know is that quantum physics is the underlying theory that governs really a lot of things around us. It governs, for example, the connectivity of a material, it governs the strength of a material, it governs how we can create maybe a new pharmaceutical, a new drug, so quantum physics is a really, really, all encompassing theory. There is, however, a big problem and that is as soon as you try to solve the equations of quantum physics, then if you look at any kind of realistic system that actually a normal computer isn't capable of solving these equations anymore, then so what do you have to do is you have to bring a lot of approximations which in a way then defeat these equations altogether. That means we have to go to the laboratory and do experiments and it takes ten years to develop a new pharmaceutical because you can't just throw things on a computer and just solve it. Computers are simply not powerful enough. So, this is where quantum computers come in. Because quantum computers operate such as nature, so according to the same physical principle, they enable us to solve exactly some of these really really interesting problems and they enable us to gain a whole different understanding of nature, of the world around us because they allow us to assimilate the world somewhat exactly as it actually works under the hood, how a material behaves or how any of the interesting things that you'd like to understand, how does that work under the hood? A quantum computer can assimilate that.

I: That is fascinating. So, if I'm getting this correctly, we're actually harnessing quantum mechanics of the quantum world to understand the quantum world.

R: This is exactly right. This is why it makes perfect sense. I shouldn't have to convince anybody of the usefulness of the quantum computer because exactly as you say, we literally are using the quantum world to assimilate the quantum world, but that's not everything. So, this is, for me personally, why I'm most enthusiastic, decided twenty years ago I'm just going to build a quantum computer and I will not rest until that has happened, but there are some other algorithms that actually are built on the strangeness of quantum physics but can help us to do other things. Like, optimise things, for example break encryptions and there are algorithms to enable us to factorise a really large number. You ask yourself, "why would anybody want to factorise a large number?" So, if I ask you to factorise nine, you can do that in your head, it's three times three, right? But why would you want to factorise a large number? Turns out factorising a large number enables you to break all current encryptions. For example, if you need to put your credit card details on the internet then by breaking this encryption will require you to factorise a very large number and there is an algorithm for quantum computers that can actually do this very efficiently, much faster than a conventional computer. So, this is one example, where a quantum computer has an algorithm and enables it to solve a real-world problem. Other real-world problems, a quantum computer can be really good in.

I: So, a quantum computer algorithm can solve cryptography but I am assuming we can also make things protected with a quantum computer, it's not just attacking.

R: I shouldn't say quantum computer is…it breaks cryptography. This cryptography, which is actually very different to quantum computers, and that is a means to use the laws of physics to transmit information truly secure. So, your security is backed by the laws of physics, by quantum physics and that type of encryption can't even be broken by quantum computers either because you're really safe by the laws of physics and that's something where really quantum physics can help.

I: That is fantastic. Obviously, there is a lot of potential and there are several examples of working quantum computers still with their own limitations. There is IBM, Google, Japan has recently unveiled their own quantum computer. Many countries are working, many universities are working in creating quantum computers but they are still major challenges to make. The quantum computer that can solve all these problems are reality. Why is it taking so long to make progress? What are these challenges?

R: It's very important to understand where we are actually with quantum computers. Let me start by you could right now go on the internet and you can log yourself into a quantum computer, IBM quantum computer for example, and you can actually play with that machine. Now, the only challenge or the only issue with that is that the quantum computers which we have nowadays, they're very small-scale quantum computers. They have a handful of qubits, maybe 50 or 100. That's the limit. Nobody has built quantum computers more powerful enough. Now, what you should know is that many of the really interesting applications of a quantum computer actually require not 100, not 1,000, but hundreds of thousands of millions of qubits. This is what you have to realise when wanting to solve really really interesting problems, you need much more powerful quantum computer that can host many more qubits. So, there are different technologies, different hardware platforms in order to build such a machine. You've named already one of these hardware platforms, super conducting qubits, and that's the hardware platform which is used by IBM and Google at the moment. That has been a very successful hardware platform but it comes with one big challenge and that challenge is that you need to cool that machine, the microchip, all the way to absolute zero, so millikelvin temperatures. So that's -273 degrees Celsius. But at such a temperature the cooling powers and the ability to cool a large object is actually very limited, so even the very best refrigerators have only ability to provide microwatts of cooling power. What is a microwatt? You know, for example, maybe your lightbulb at home how much watts that has, it's a few watts, ten watts, so these refrigerators have only microwatts of cooling power and because you can't have much cooling power at that temperature, it means it will be very challenging to scale such a quantum computer to the required number of qubits to solve some of these really important industry problems. So, what we've done at the University of Sussex and in the company, Universal Quantum, is utilise a different hardware platform and here we use charged individual atoms, or ions and so these atoms are held on a silicon microchip like my hand and each ion levitates above the microchip. Now the really cool thing about this technology is actually it's room temperature technology and we are using a slight cooling but we do that actually for the classical electronics. Just as we have to cool your conventional computer when you overdrive it. So, we cool this microchip slightly, but at the temperature we cool it to we have hundreds of watts of cooling power. So, compare microwatts, ten to the minus six watts, we have ten to the three watts, so that tells you something about the ability to scale that to large qubit numbers and this is something, scaling is really so important for quantum computers. You asked the question, so when will we have real quantum computers and when will they work for us. To answer your question, I really need to talk about how do we get to these really large qubit numbers? Just actually a few weeks ago, we reported a really big demonstration that takes us on the road to achieve that. What we managed to do is we connected two microchips using electric field links. So, we actually put them close together and we connected these microchips using electric fields and we were then able to transport individual qubits or individual atoms from one microchip to another microchip. We did that both with such speed and with such a small area that it would enable us to actually build large scale quantum computers that don't just have 100 or 1000 qubits but enables us to really build large scale quantum computers that could have 100,000 or million or tens of millions of qubits. So, coming back to your question, this is what we need to do right now in building quantum computers. We need to come up with innovative solutions of how to scale these tiny proof of principle machines to qubit numbers that are required to run some of these really interesting industry applications on quantum computers. This is what I am extremely passionate about, all my career at the University of Sussex and in 2018 we founded this company, and the headline of all what we do here at Sussex and all that we do at Universal Quantum is to devise solutions that really enable us to build practical quantum computers that are powerful enough to solve some of these really interesting industry applications, and we do that by aiming to scale to large qubit numbers.

I: So, I think just a couple of more questions. The next one will have to be, you're now, I am assuming, testing scaling this up? You're testing, what is the timeline that you envision?

R: I guess the really exciting news is now that we're getting now kinds of a phase where people in research groups did small proof of principle experiments to now a time where we employ some of the very best engineers to come up with technology solutions that are scaled. So just to give you a feeling, so when you have your laptop, I guarantee that the chip in your laptop is not built by a PhD student in a university research facility. If that would be the case, we probably wouldn't be on this call right now because there would be something wrong with the computer chip right now. Your computer would be constantly in repair or something. Your computer chip is made in a silicon foundry where all the processes are so perfect and accurate in order to allow you to scale this chip in such a way that it becomes fully reliable. So, for me personally, this is a very similar thing in my journey to build quantum computers. I started in 2005 and I said, I am definitely going to build quantum computers and I started doing that in the research group where we did small proof of principle experiments with just a couple of qubits in order to then demonstrate all the physical phenomena that we predict will be required in a quantum computer actually do work. So, we've ticked off a lot of these demonstrations. Then in 2018 we said, okay now let's do this properly. We started a company and the company now works with foundries, with places to make these silicon microchips really professionally. We have some of the very best engineers from all around the world, so I am immensely proud to work with some of these really truly amazing people to actually really design and engineer microchips that scale to large qubit numbers. This is where we are right now with building practical quantum computers now, these machines are in industrial production. It doesn't mean next year you're going to have at home, in your basement or under your desk a quantum computer. It's still integrating, all the engineering challenges will take time, and it's also very costly. So, working with a foundry like that, doing some of these engineering tasks costs a lot of money. So, this is another reason why you can't do this as a university research group, there is no grant available sufficiently large to do something like that. You really have to get a company to do that. In the company, what we are doing now is we build the first test machines, then we can integrate all the engineering into a single machine. I'm super proud to tell you that just recently we have been awarded by the German Space Agency one of the largest ever government contracts in the world to build two demonstrator machines based on the technology I have been telling you about. We have built them now in Hamburg, so there are going to be two machines which are going to have all the specifications to really show customers use of quantum computers, that all these concepts really work and they can all be integrated into a single machine. So that's the first step, then beyond that we're going to go to scale, so build more of these silicon quantum computing modules, add them together, as I mentioned before by making electric field links. Even the machines we have built in Hamburg we're already going to demonstrate and show off some of these really cool electric field link technology able to scale us up. Now, people always ask me, so when are we going to have a useful quantum computer? I am always going to reply with my same answer. I am going to ask them, so when do you think we had the first useful conventional computer? That's my question I immediately shoot back. Some really clever people then have to think for quite some time and think, when was that? Some people say in the sixties, but the really clever people look to history. They say, actually, it was 1945. In 1945, the English Army decided the second world war by building the first computer that could break the German Enigma code and that was arguably a reason why they could win this world war. So, you can see, in 1945 we have the first high impact application of a conventional computer. When I grew up in the 1970's I learned typewriting on a machine typewriter. I didn't have a computer at home because computers got to all of us much later, like in the early eighties or something, everybody started to have a computer. So, as you can see that if I had asked the question, when did we have the first computer? If I ask myself, it would have been in the eighties, if I asked an historian, they would have said 1945. We really have to qualify that question for what applications? For calculating projectiles or for breaking encryptions, we had a classical computer in 1945. For me to do my word processing or to get a ticket at the train station, certainly not even in the seventies. So, the same thing applies to quantum computers. What we are going to see is in the next five or ten years we're going to see one first useful application for a quantum computer and that might a really high impact application that will change certainly everything maybe in one particular industry sector. Then we're going to build more powerful quantum computers and not just that we're going to build more powerful quantum computers but we also work on the algorithms, so the software, because that is equally important for a quantum computer. The way quantum computers work is by making use of these very strange quantum phenomena and in order to really fully capitalise on these phenomena the software has to work in one particular line in order to really enable you to make full use of that. So, for every problem we want to solve with a quantum computer you don't just have to have a quantum computer, you also have to write software that you also need to develop. So, what we are going to see over the next five or ten years is people are going to more and more develop the software. As a company, for example, we work now together with others on the first quantum computing operating system, we work with theories on solving really important problems like, for example, simulating the FeMoco molecule. That's an example we've just recently worked on. The FeMoco molecule is important for nitrogen fixation and nitrogen fixation is really important when you want to make fertilizer. It turns out 2 percent of the worlds' energy is right now being used for making fertilizer. If you can make nitrogen fixation a little bit more efficient, imagine how much energy you can save? That's one problem for a quantum computer. Now we've just done a lot of work trying to exactly understand what are the resources required for that and now that we can build machines for that purpose. I'll give you another example. So, we work right now with Rolls Royce towards building quantum computers that are capable of developing better aircraft engines, so more fuel-efficient aircraft engines. This is all about fluid dynamics, and so using quantum computers to really simulate the flows within inside such an engine, and that will have a big impact, but we first up need to start understanding what's required, the resources required and then we can streamline the development of the machines so we get there and maybe, hopefully, get there a little bit quicker than if we wouldn't have prepared ourselves for this particular application. So, you're just going to see more and more applications like this coming through one after the other. If we're going to have this interview in two years, in five years, or in ten years' time again. There will be a much more powerful quantum computer than there is now, but there will still be many applications for quantum computers that are completely inaccessible by the machines we will have available then. So, we're always going to make more powerful machines, but I think the first really cool and really interesting applications we're going to see in the timescale of five or ten years and then in twenty years there are going to be yet another array of really interesting application that will slowly grow as the performance of these machines becomes more and more powerful.

I: That was fantastic. I guess that leaves us with our last question, the big question. You have already answered will many examples, maybe you can give us another one. How can quantum computers change the world? You have described all these applications from more efficient engines, more efficient creation of fertilizer, pharmaceutical technology. Is anything more that we can expect with these machines?

R: When I give lectures sometimes, I use a very old newspaper article, again about conventional computers and they always say in that newspaper article when they talked about first computers, the mathematicians said there are no problems complex enough for a computer to be needed. Engineers said some of the problems are way too hard to be ever solved. Famously, I don't know if that's true, but I've heard the head of IBM once said there is a broad market for four computers. That man was a very smart person. He was on the very frontline, on the edge of really building this technology. The reason why I am telling you that is because when technology grows, we are extremely naïve about what that technology can actually do. So, has to be a very much in the baby steps right now of building these machines and it's absolutely certain that we only just started to scratch the surface of the true capability of these machines. The same way as in 1945 we didn't know anything about what conventional computers would do. We also didn't know it in the 1970's. I have a watch right now on my hand with which I can pay, I can make a phone call with my watch. Now I said this to my mum and she couldn't believe it. She said, what do you mean you have a watch you can make a phone call with? So, what I'm trying to say is don't expect or think that somehow, we are so smart, and even people on very front of quantum computing, they can't actually predict what quantum computers can do. I can tell you right now what algorithms are known, I can tell you right now my assumption of maybe how far it will take us to these applications, but I can equally tell you that a good friend of mine told me not so long ago, that even five or ten years ago you couldn't even get a job at a university when you said you're going to develop quantum algorithms because nobody even felt that's worthwhile because people didn't think we could build such a machine. So, in the next five or ten years you are going to see plenty of new applications and when we talk now about simulating molecules and drug discovery or breaking encryptions, in ten years' time we are going to talk about plenty more things and plenty of different things. Quantum computers are a very very powerful new tool, think of it that way and it's in our hands what we can do with it. I think, probably for me, from an intuitive point of view, the most amazing thing about a quantum computer that will help us get a grasp of what is there in the future. Is it the fact that quantum computers can simulate nature as it is, according to the very underlying phenomena and equations it is actually governed, and that's a very powerful thing. If you can understand the world around you and simulate it exactly using such a machine, you can only start to imagine the consequence of the type of understanding, knowledge, and grasp you can obtain for a lot of different things. Maybe we can, using quantum computers, understand how we make a room temperature super conductor. Imagine the type of energy savings you could get with that. Biological systems are very hard to understand because rather than working on a similar atomic basis you have to have these much bigger systems that are extremely hard to simulate. Quantum computers may hold an answer of some of these questions, even biology. Some people say we might be able to simulate a protein folding that may help us understand the reason for dementia or things like that. Now, what I don't want you to think about is that a quantum computer is some kind of magical wonder machine and once we have one, we just press a button and it's just going to solve all the problems. Quite the opposite. Quantum computer is an extremely powerful tool, but we need to develop how to use that. You need to understand the algorithms. So, there is a lot of work required and you're going to see, using this really powerful tool, a lot of different applications and we already understand why now, these applications range from the financial sector, the chemical industry, from the pharmaceutical industry, optimisations, image recognition, quantum machine learning. So, you can see that literally any sector will somewhat be affected by quantum computers, but not immediately, but it will slowly happen and we see already now banks working very closely with quantum computing companies, insurance is working with quantum computing companies, car manufacturers, even rail companies work with quantum computing companies in order to make better timetabling. So, you can see that this is going to go everywhere, but it will happen gradually but it will be an extremely exciting future and maybe personally, I have something else about quantum computers which is close to my heart. When I was very young, in primary school, I took a decision in primary school that I was going to be science officer on the Enterprise. I think I was grade three, or grade four. So, then I asked my mum, what do I need to study to be science officer on the Enterprise and my mum said, it's probably going to be physics or astronomy. So, I am one of the few people who took my decision to a degree already in primary school. The reason why I took that decision was because I was blown away by some of the strangeness that science would hold, and I think quantum computers and quantum technology in general holds a similar fascination for people who learn about it. Like, in an object, if I do something to an object here in my office that can instantaneously affect something that is at the other end of the universe, this is entanglement. This kind of strangeness really affects people when they hear about that and they really appreciate the amazingness of quantum physics and so I think quantum computers are a really powerful tool to enthuse people that studying STEMs subjects that exploring the world, exploring entanglement, superposition is one of the really coolest things and science is by no means an end. We are just getting started to explore some of the really cool things. So, I can say to everybody who listens to this right now, if you are just about to think should I do a STEM subject at school; should I enrol in physics or chemistry? Don't think this is all done and it's all the boring stuff your teacher tells you about. It's actually really cool stuff, its entanglement, it is teleportation, real teleportation. We can do teleportation in our lab right now, with individual atoms. All that cool stuff you've heard about in some sci-fi films, many of that stuff is actually true, you can work on that. I feel something with quantum technologies and quantum computing really exposes the amazing magic and the tremendous potential in getting people enthused and engaged with sciences.

I: Thank you so much for the deep explanation about everything quantum computers. Thank you so much for your enthusiasm for both making it realistic about the timescale of quantum computers and thank you for giving us all this hopeful energy about studying STEM subjects.

R: Thank you very much. I really enjoyed it and it's really the coolest time to be in quantum computing. I couldn't be more enthusiastic about it. It's really amazing stuff we do everyday in the lab.

I: Wonderful. I think the last thing I can say is, live long and prosper.

R: Thank you very much. You too. Thank you.

Quantum computers have immense potential but challenges still remain before that potential is realised. Clearly, it is an exciting time to be working in this discipline and we can't wait to see what new breakthroughs will happen in the next few years.

Thank you for listening to The Big Questions. Head over to iflscience.com for the latest and greatest science headlines. The music in this episode is credited to Audioblocks.com. See you next time.

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