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

I: Computers and supercomputers play a pivotal role in our lives. From the most basic telecommunication to the design of the most advanced technology we rely on these instruments to push beyond our limits. But what about their limits? For as much as they get faster and faster, conventional computing technology won't improve forever, so what happens when they reach those limits? Are there ways to avoid them? To help us answer this crucial technological query we are joined by award-winning engineer, Mazhar Ali, Associate Professor at Delft University of Technology. His work is actually pushing those limits.

Hello Professor Ali, thank you for joining us. Can you please tell us about yourself and your work?

R: Okay, so, my name is Mazhar Ali, of course. I am a Professor at TU Delft in the Quantum Nanoscience Department which is part of the faculty of Applied Sciences. I'm also part of the KIND, the Kavli Institute for Nanoscience at Delft, which is a very important organization that does nano and quantum research, in particular related to some of the big questions. We say we try to answer the biggest questions of the very small.

So, let's see. My group here focuses on what we call the three Q's: Quantum materials, or their quantum properties, or making quantum devices. The idea is they're a class of materials called quantum materials that are so-called because they're not best described classically. It's a bit of a broad definition but it has a really important point in that they're manifesting quantum mechanical properties often at macroscopic scales, which gives us the opportunity to try to tap into those quantum mechanical phenomena beyond the effects, try to actually take advantage of things like quantisation nowadays.

So, it's really something that's taken off in the last 15, 20 years. Graphene is arguably probably the most famous quantum material I think everybody knows about. It manifests all kinds of interesting properties, particularly most famous for hosting electrons that can travel near the speed of light, ultra-high mobility, which is now something that is found in a lot of other materials that share that common trait. It's called Dirac's semimetal. So those are examples of quantum materials and that's an example of some of the quantum mechanical properties. Another famous category is superconductors, which is relevant to what we have done, and the trick there is that instead of electrons traveling around independently through a material they are actually able to pair, which is counterintuitive because normally you think of electrons as essentially being repulsive to each other, which they are from the Coulomb's force. But there are scenarios in which they can actually overcome that repulsion and end up having an attractive potential, usually through some mediating particle, like a photon, and in the end they're able to pair and by pairing they are not acting as fermions any more and stuck with fermionic statistics, meaning only two particles for every energy level, they're acting more like bosons, which have the trait of having essentially an infinite number of particles possible in one energy level, as in you can have identical particles, where with fermions you can't.

The important point of that is that it lets you basically create an energy gap between this energy level with all these infinite number of particles and the next energy level. So that becomes a superconducting energy gap, and the point of that gap is that in order for something to stop superconducting it has to hit something with sufficient energy to jump that gap. So, this gap is like a barrier and it's like a protection from scattering because something has to hit it with enough energy to overcome that barrier. So, because of that, these superconducting materials can essentially have electricity travel without any resistive loss.

You could make superconducting wire from here to the moon, for example, and as long as you kept it cold you would actually lose no energy in the transmission, which is a big drawback for today, even though we have very good copper wires all around the planet transmitting electricity, we actually do lose a very significant amount of energy just in transmission. So, superconductivity is a very important property and its fundamentally coming, as you heard, from a quantum mechanical state. So those are quantum materials and quantum properties.

Lastly the idea is to make quantum devices. So, to take these types of materials, take advantage of those properties and make things integrated into computer chips, for example, or other types of electronics for next-generation technologies like, for example, probably the most popular thing I could talk about is quantum computing which, case in point, actually is still taking advantage of superconductivity. That's another place superconductivity is important. The qubit today, IBM and everybody's qubits today are still superconducting qubits and at the heart of that particular technology is a Josephson Junction, which is the junction of two superconductors across a non-superconducting barrier. It's like a hamburger where the two buns are superconductors, and the meat patty is something that just wasn't superconducting. The trick there, the point of doing such a thing is that the two superconductors, again, being quantum mechanical we can talk about the wave function describing the conductivity, essentially in the two superconductors, and those wave functions of the independent superconductors have to talk to each other through that non-superconductor so they can interfere with each other.

That interference is super important actually, and it gave rise to the SQUID, the Superconducting Quantum Interference Device, and the Josephson relation. So Brian Josephson, when was just a grad student, he was 22 or 23 years old and he wrote down famously, he did almost like a homework problem style, he wrote down what he thought would happen if you took the scenario of two superconductors across a non-superconducting barrier and he found that you could still superconduct because the wave functions constructively interfered then they will be able to have these Cooper pairs, this superconductivity across the barrier as though the barrier wasn't even there. But when they are out of phase, then it would turn off, the superconductivity would die, and how could you tune the phase? That was a very important finding. The phase is modulated by a magnetic field so all of a sudden you could have a device where you could have superconductivity on or off as a function of a very small applied magnetic field. So, if you were measuring whether it was superconducting or not and you wanted to be able to tell if there was a magnetic field around, let's say even the magnetic field of your brain, it's so sensitive. It's ten to the minus, like fifteen teslas, a magnetic field generated by your brain. This device can be so sensitive that it can detect that because it would turn off the superconductivity by making the wave functions misalign. From quantum computing to magnetic resonance imaging, which is actually the same thing as what I just talked about, this magnetic field detector, superconductivity is super important.

I: What a tour de force of everything that your institution is working on and many other researchers across the planet, but I am particularly interested in one of your team's developments. You have created a one-way superconductor, which we think is an incredible breakthrough. Can you tell us a little bit about that and its potential impact on computers?

R: Everything I talked about and superconductivity, in general, has always been two-way. The term we use in the field is reciprocal. Now, reciprocal versus non-reciprocal, as in one-way, is a very important concept in electronics in general. So, the idea of reciprocity is this: something that flows forward also flows back in the same manner, that is what it means to be reciprocal. What it means to be non-reciprocal is very simply that something that flows forward does not flow backwards necessarily in the same way. While reciprocity is very important in physics it's also very important in technical applications where it governs a lot of the properties of devices that you use. However, non-reciprocal components are equally important. You may not realize it but every piece of technology you are using, in particular to do this right now, you know, you're on a computer using a monitor as well as wireless transmitters etcetera. They all have non-reciprocal components in them.

Probably the most basic example of a non-reciprocal component is a diode. A diode literally conducts electricity forwards and if you reverse the voltage within certain limits, it won't conduct electricity. The most famous example is the pin diode. The semi-conducting diode. That was the precursor to semi-conducting transistors and basically all semi-conducting electronics thereafter. So, non-reciprocity is super important. But superconductivity was always reciprocal, two-way. For a long time, it's been desired to try to figure out a way to make a one-way superconductor, to make a non-reciprocal superconductivity, especially without requiring any external modifications like an external magnetic field or something. You don't want to have to control it with a third or fourth knob to be able to do so, to be able to control it on a chip. That's basically what our team did and what our trick essentially was to use a Josephson Junction. We made a special type of Josephson Junction, a quantum material Josephson Junction, so we call it a QMJJ, it's the term we are starting to use.

So, what we did, we took two superconductors as the buns, but this time as the burger instead of a classical material we used one of our, let's say, special 2D quantum materials that has some intrinsic symmetry-breaking properties that when we made this device, this junction, it as a whole, broke inversion symmetry and time-reversal symmetry. The key to becoming non-reciprocal was that you have to break symmetries. If something, again, moving forward is the same moving backward it means it's locked together, primarily by time-reversal symmetry because you can imagine moving forward and backwards as forward in time and backwards in time.

I: **It's like if you were rewinding a video camera, if you were seeing backwards, it still looks the same it would clearly be symmetrical. Like, if an egg is rolling off a table and break on the floor you would know that that doesn't work. You don't experience eggs jumping off from the floor and coming together.**

R: Right, there you go. Exactly. So, in order to unlock the two-way superconductivity into being one-way we had to break symmetries, so we took advantage of these quantum materials that intrinsically broke these symmetries, stuffed it in between two superconductors, made our Josephson Junction, and there you go, it worked. The big thing is that we were able to do this without requiring an external field. There is no external knob. So that was why this was really important because it means we can start making semi-superconducting devices that are analogist to semi-conducting devices now. We can make superconducting diodes which is what we did, we make a Josephson diode. Hopefully, next step we can make superconducting Josephson transistors in the same way and so on and so forth.

So that overcomes a lot of the problems that semiconducting electronics have hit, which have been that you can't go faster anymore. You've noticed your laptop maxed out at 3 or so gigahertz, 4 gigahertz maybe a decade ago. We don't really increase clock speed anymore. We have been making more and more devices in smaller and smaller footprints, but we can't go faster and there are a few reasons for that. One important reason that computing plateaued is just that we generate a lot of heat, we waste a lot of energy. So, if you had superconducting devices that were literally not having resistance in half the time, let's say in the 'on' state, then there is a potential to save a lot of energy and it also depends on the power that is needed to switch the superconductivity on and off. We found that we were able to do this at roughly 100 times less power than is currently used in semiconducting chips.

In theory, and this is the other really fun part…actually it's not just theory, you know, about 40 years ago at IBM they had started investigating a Josephson Junction computer. They thought even a long time ago that superconductivity would make very fast and energy-efficient computers, let's give it a try. They really did and they made these devices and they found, first, that they could switch almost a terahertz speed, that's 300 or 400 times faster than today's computers, they were able to switch these devices, but they found that one big problem which was superconductivity was reciprocal and they had a lot of error when trying to do the switching. The bits weren't as robust as the semi-conducting versions because of the non-reciprocal nature, like I said, of the semi-conducting electronics based on things like diodes and transistors. Since there was no superconducting version, they were just switching basically reciprocal devices and when they would try to turn it off, if they were even a little bit inaccurate, which you know, is life, then they couldn't turn it off and they would have an error. So even though they were able to go at almost terahertz speeds they had an error and they specifically said, 'Boy, it would be great if we had a non-reciprocal superconductor'. So here we are 40 years later solving that problem and saying that we can definitely switch at way lower energies and now we are going to try, in a lab, to recreate those experiments from long ago using our one-way superconducting diodes or let's call them non-reciprocal superconductors and see and confirm, hopefully, that we can still switch at terahertz speeds as well. In which case, we're off to the races right? It basically resets Moore's Law. Rather we can start scaling speed up again, even though you have to cool a superconductor down you don't have to cool it down so much that it offsets the energy savings.

I: **That was very intriguing, and you have hinted at our big questions with the mention of how computers have plateaued and Moore's law. So, the question is, what do you consider to be the current limits of traditional computers and supercomputers?**

R: So, there are a couple I can rattle off that are pretty well known, right? First off, there's what is a power density? There is an issue with how much heat we can deal with in a certain area in terms of getting rid of it. Roughly 150 watts per centimeter square is the air cool limit. So, beyond that, if you were trying to make a computer chip that was generating even more heat than that then you can't air cool it, you need your liquid-cooled super fancy computer tech. Then maybe you could overclock it, I suppose, and go even faster, get up to 5 or 6 gigahertz.

But with the air cool, that's part of why we end up with that clock speed limit, one reason is trying to get rid of all this heat very quickly. All these things are interrelated and related to that is the so-called 60 millivolts per decade. So basically, it takes a certain amount of voltage to trigger a certain order of magnitude change in the current you're measuring across your device. What I mean by that is if you have a zero state and a one state, in order to not have very much air you want them to be as far apart as possible. You want your zero state, or let's say 'off' state, to maybe be really highly resistant and your 'on' state to be really low resistance.

Then there is a question of in order to switch between these two states how much does it cost you? That number is roughly 60 millivolts per order of magnitude. That's pretty good, but now you see why it's tied to the amount of heat generated. If you could change how resistive you are for less than 60 millivolts per decade then you would generate less heat and you could go faster or stuff more down. All of these numbers are interrelated. So those are a couple of reasons why traditional computers have got pretty limited, especially in terms of workstations.

Nowadays, frankly, a lot of the real computation isn't done by us as terminal users, they're done in huge processing centers and we're just people using terminals that are connecting over the fact that we have these high-speed communication capabilities, we send requests to places to do the computation and then we get the answers back. Those are often these supercomputers, which is half a logistical problem as opposed to a pure tech problem because it's really like stuffing in all these as fast as we can go computers into racks in cooled buildings located in places that offset the cooling and energy costs of such a building. So ideally, somewhere up in the Antarctic or the Arctic would be a good place to put a supercomputer but not great for the planet, frankly. Yeah, I guess that's where I would stop there, those are some of the limits of the traditional approach, especially the Von Neumann style of computing which is what these are.

I: **And you and your team have already worked on one potential breakthrough to push beyond those limits. Do you have any insights on any other breakthroughs that could push past those limits, if there are any?**

R: Oh yeah, so we have a route. We are trying to basically continue or extend the Von Neumann route using our special materials and our special junctions to allow that route to go faster and be more energy efficient. So that's a way, but there are other ways that are trying to change the formula completely as it were, for example, quantum computing, which is just fundamentally different in how it works which is really about approximating a two-level system as best we can. Like I said, using superconducting qubits and storing information and processing information rather than in zeros and ones, in a superposition of all states in between to try essentially to be able to map an entire problem space much faster. To dramatically simplify things. That is a very good approach and very powerful approach, and we are starting to see it reach relevance. It's getting there. There have been some setbacks recently of course but it's still progressing pretty well.

There are a few other different approaches. There is neuromorphic computing which is a very interesting approach that is related to trying to approximate more how our brain works with maybe the biggest difference there being that, for example, the type of computing I was talking about is three-terminal based. There's an in and out and a control. Something that controls whether you're going in or out. Your brain works a bit differently. It's really two terminal. There is just an in and an out but whether or not a signal coming in makes it to the out is entirely dependent on the signal itself, which is quite unique. There's not an extra control, the signal is the control. Above a certain threshold, the signal passes through completely and below a certain threshold the signal is critically damped. This is basically whether or not your neuron 'fires'. That is very different from the other approaches, so it's a very interesting question as to how we can approximate this because it's very tied to joining together many of these types of devices, neurons, and we found above a certain number of connections we start to get emergent behavior where it acts no longer just like the sum of its parts. There is more coming out than going in which is a very interesting scenario that frankly the whole field is still trying to wrap its head around. Then there are a few others that I can throw out. Reservoir computing, which is an interesting alternative route but yeah, I'd say right now the front runners are quantum computing and neuromorphic computing. That's my bias I suppose and hopefully now our superconducting non-reciprocal super connecting computing comes up and hopefully it comes up very fast. I think it will.

I: That sounds fantastic, and I hope it does come really fast to counteract some of the limits that current computers have. Thank you very much for taking the time to speak to us today.

R: Of course, thank you very much for having me.

Thank you for listening to IFLScience, the Big Questions. Head over to www.Iflscience.com and don't forget to sign up to our newsletter so you don't miss out on the biggest stories each week. Until next time.

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