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We must set the bar high and tell students we expect them to jump over it

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Abstract

The 2018 Australian of the Year is quantum physicist, Michelle Simmons. Below is reprinted the address she gave on Australia Day, 24 January, 2017; she was elected FRS in May 2018.

His Excellency, the Governor of New South Wales and Mrs Hurley; the Honourable Gladys Berejiklian, Premier of New South Wales; chairman and board members of the Australia Day Council of New South Wales, distinguished guests, ladies and gentlemen. It feels very odd for me to be here today.

I went to a pretty rough school, a south-east London comprehensive. Out of the 200-300 students in my year, only 16 of them did A Levels (that's the equivalent of the HSC); and, of those, only two passed.

I have always been an introvert. As a child, I hated the limelight; I still do. In my English literature lessons at secondary school, our teacher used to go systematically around the class to encourage each of us [to learn] to read out aloud. Such was my fear of public speaking, however, that instead I quickly learnt to shift desks every day so I made it through the whole four years without having to speak up once.

What's more, growing up in that part of England, I was not raised within a culture that said: "It would be essential to go to university, let alone leave Britain and set up a life at the other end of the earth."

So, if someone had told me 30 or 40 years ago that I would one day be asked to deliver an Australia Day address, you can imagine I would never have believed them.

Yet life is full of ironies. In my south-east London home, when I was a little girl, I had an older brother Gary who, whenever I got a little too annoying, used to joke with me: "One day I am going to buy you a one-way ticket to Australia."

As things turned out, he didn't need to because, in 1999, I came here of my own volition; and in 2007, I became an Australian citizen. When I say that, all the little hairs on the back of my neck stand up and I feel really proud to be Australian.

For some reason, though, I always kept that plane ticket that brought me over here, and just a year ago I had it framed and sent to my brother for his 50th birthday. Ironically, and a little sad for my father, my brother now lives in the US and I live here and I joke with Gary that I got the much better deal. Only, for me, it's not a joke. I really believe it. I genuinely do believe it is better here than over there. And the 26th of January, Australia Day, is one day when I can say this wholeheartedly without feeling as though I am bragging.

Today is a day for celebrating Australia: the wonderful country it is, and all the opportunities it offers. And to this end I want to share with you why I came here — and why I choose to stay. Along the way, I hope to describe to you why I think Australia is a great place to be for anyone interested in scientific discovery and innovation.

I also want to leave you with a sense of why Australia is well placed to realise the next revolution in computing — the quantum revolution.

But let me begin by telling you how unexpected it was for me to become an Australian. A physics PhD is, in a sense, a passport to the world, and I was lucky in my early career because I gained some terrific experience in excellent research groups in the UK. I went to Durham University in the north of England where I was able to design and build electronic devices — solar cells for capturing the sun's energy. I then went to Cambridge University in the south of England where I learnt the complexity and fragility of discovering new quantum effects. This is the weird physics that emerges when dealing with [the] world as it gets very small — in particular when we get down to the size of individual atoms (the fundamental building blocks of nature from which we are all made), which are approximately a million times smaller than the width of a human hair.

Working at Cambridge, in the semiconductor physics group, I learnt to design, fabricate and measure my own samples — three completely different skill sets, a unique combination that really makes you the master of your own destiny. But there also came a point when I wanted to find a more ambitious project to work on than the very fundamental physics they were doing there. Specifically, I was drawn to the technological challenge of trying to create new devices that had never been made before, where each atom had to be put in place to engineer a particular effect — in essence to create electronic devices at the atomic scale.

It was this that brought me to Australia.

Back in the 1980s, IBM invented a new kind of microscope, which, for the first time, enabled humans to "see" on the atomic scale. These are fabulous tools — giant stainless steel contraptions that fill a room with a vacuum inside akin to that in outer space. As with so much in science, the machine itself looks incredibly complicated from the outside, but the principle of its operation is simple. They are built around a very fine metal tip, which we bring down, under electrical control, towards a sample surface. When it is in close contact with the surface, electrons tunnel from the tip to the sample and create a current. We measure this current and keep it constant as we scan the tip across the surface, hence the term "scanning tunnelling microscope" (STM). We scan the atoms across the surface rather like a TV screen to build a topographic image of the surface.

The invention of this microscope enabled scientists to see individual atoms for the first time and to observe how the arrangement of the atoms on a surface was completely different to those in the bulk crystal. When we cut the surface, we remove the atoms above, causing the atoms at the surface to rearrange, moving closer together to lower their energy. Since most of life's processes occur at surfaces or interfaces, being able to actually see atoms and understand how they behave differently at surfaces was a huge breakthrough. This was, then, an incredibly important discovery. The STM, as a consequence, was one of the fastest inventions to win the Nobel Prize, just four years after its discovery in 1984.

But seeing atoms was just the beginning. In the 1990s, IBM found a way to exploit this technology to go one step further and to actually move atoms around on a surface. Using an early scanning tunnelling microscope, they formed the world's smallest logo — the letters I, B, and M — out of atoms of xenon on a copper surface. That was a great demonstration of technological prowess — to be able not just to image atoms but to manipulate them. But it is one thing to push a few atoms around and make a logo, and quite another thing to take that technology and create an electronic device where the active, functional component is a single atom.

It was in the hope of realising this dream that, in 1998, I applied for fellowships in Australia and in Cambridge, and for a faculty position at Stanford in the US. As a young academic we are taught that the prestige of the institutions that we work at is very important. However, when I was offered the Australian fellowship, I accepted immediately and pulled out of the other two processes. It was a decision, I'll be honest with you, that perplexed not only my colleagues overseas, but also many Australians. When I arrived here, people would ask me, "Why on earth did you come?" But the choice was easy.

In practical terms, I did not want to stay in Cambridge. The structure was too hierarchical and the research was esoteric. Who cares if you can answer a fundamental physics question? I wanted to build something — something that could prove to be useful. The British research system also offered that wonderful possibility of working with pessimistic academics who will tell you a thousand reasons why your ideas will not work.

American culture was more appealing than this, but it too had its limitations. The US offered a highly competitive environment where you would fight both externally and internally for funds and be beholden to a senior mentor. Their system also restricted responsibility for the early-career researcher, whereas Australia offered the freedom of independent fellowships and the ability to work on large-scale projects with other academics from across the country.

Seriously, there was absolutely no competition. To this day, I am delighted with my choice and firmly believe that there is no better place to undertake research. Australia offers a culture of academic freedom, openness to ideas, and an amazing willingness to pursue goals that are ambitious. And the results speak for themselves — we have achieved tremendous success in our endeavour, largely because we gave things a go that the rest of the world didn't dare to try, as I hope I will explain.

When I moved to Australia, back in 1990, silicon device research was focused on Moore's Law. Have you ever noticed that every year your computing devices are getting smaller and faster? Many years ago, Gordon Moore, the co-founder of Intel, noted that the number of transistors on a silicon chip was doubling every 18 months to two years. In practice, this meant that each individual transistor had to be decreasing in size at the same rate. The amazing thing about this law is that in the late 1990s you could plot the size of future transistors as a function of time, allowing us to predict that by 2020, we would reach the level of individual atoms.

With the industrial world focused on the iterative process of making devices smaller and smaller each year to maintain their margins, back in 1999, with a few others I hatched a plan. The plan was to focus on adapting the technology that existed to image atoms to see if we could make a functional electronic device where the active component was a single atom — in other words to leapfrog the global IT industry and make devices on the atomic scale.

This ambition was fuelled by a separate theoretical proposal coming out from Australia back in 1998 which suggested, if we could control things at the atomic scale, then we could make a completely new type of computer that worked entirely on quantum physics.

Such a computer is called a "quantum computer" and is predicted to bring with it an exponential speed-up in computational power. This is because, instead of performing calculations one after the other like a conventional computer, a quantum computer works in parallel, looking at all the possible outcomes at the same time. The result is massively parallel computing, allowing us to solve problems in minutes that otherwise would take thousands of years.

One thinks here of problems where computers work on large data bases or consider lots of variables, problems such as predicting the weather, stock markets, optimising speech, facial and object recognition (such as self-driving cars), looking at optimising aircraft design, targeting drug development to the patient's DNA, optimising traffic flow and working out the shortest possible delivery routes. UPS in the US have determined that if they could shorten the distance that every one of their drivers travels each day by one mile, they would save their company $50 million per year. That's an ideal problem for a quantum computer. But this is a capability with widespread application. Indeed, a US defence firm has predicted that 40 per cent of all Australian industry will be impacted if we can realise this technology.

The potential rewards are certainly significant. I firmly believed when I arrived here that we had a viable yet ambitious pathway to get there. Yet, when we first proposed our concept, there were many critics all over the world, including senior scientists at IBM, who said that, whilst it was a nice idea, there were many technical challenges that had to be overcome. We identified eight different steps, none of which had been demonstrated. The consensus view within the global scientific community was that the chances of our getting through all eight stages were near impossible.

On top of this, to make things work, we had to combine two technologies: linking the STM (which provides the ability to measure and manipulate individual atoms) with another technology called molecular beam epitaxy (MBE) which allows us to grow, layer by layer, material to protect the atoms we have put down.

Both these instruments must operate under ultra-high vacuum, but no one had successfully combined the two, and they seemed incompatible: the STM system needed low vibrational noise to have the sensitivity to image individual atoms, while the MBE system had very large pumps to ensure high purity crystal growth — pumps that caused a great deal of vibration. It was high risk. When I told the two independent system manufacturers in Germany about the idea, they said they would make a system to my design, but that there would be no guarantee that it would work. And, for a combined system that cost $3.5 million, that was a pretty big risk!

It took two years from the design of the system to its delivery and set-up and was a nail-biting time for my career. It explains where a lot of my grey hairs started to come in. It was hosted in two specially designed adjacent laboratories but connected through the wall.

Did it work? I think I wouldn't be here if it hadn't! But to my delight it worked a factor of six better than I had hoped. And over the past decade we have systematically solved all those eight challenges that were predicted to block our way. In fact, the video[1] shows the step-by-step process we have developed by which we place and build electronic devices using a single phosphorus atom in silicon — the phosphorus being the atom on which we encode information for the atomic-scale computer.

In recent years, we have used this unique technology right here in Sydney to create a stack of world-first atomic-scale devices. We have built the world's smallest transistor where the active functional part is just a single atom beating those industry predictions from Moore's Law by nearly a decade. Following this, we fabricated the world's narrowest conducting wires in silicon, just four atoms wide with the same current-carrying capability of copper. We are systematically working towards demonstrating all the individual components of a 10-qubit system, which we hope to achieve within the next five years. Using this technique, we have shown that, in addition to placing the atoms and wires, we have built unique transistors that we can align next to the atoms with sub-nanometre precision to initialise and read out information on these atoms. We have demonstrated a concept like entanglement between the atoms where the state of one atom depends on the other — rather like a marriage. It does, however, have the added "quantum" benefit that both parties can read each other's minds. It's a beautiful world to be in.

Finally, we have moved to two-, three- and four-qubit architectures and shown our long-term ability using our STM to pattern a 1024 atomic precision array. These achievements have been published not only in the usual scientific places. My team were in the orders today and I'm very proud of them. They have also made it into *Guinness World Records* — as my son discovered one day to his great surprise while sitting in his school library.

On the back of this success, we have attracted to Australia some incredible young scientists from all parts of the world — from Europe, the UK, the US, and Asia — some of whom, I'm delighted to say, have decided to make Australia their permanent home too. We have also patented this technology extensively at each stage and remain the only group in the world that can make electronic devices at the atomic scale. Most exciting of all, though, is that we are now on a mission to build a complete prototype quantum computer for which all the functional elements are manufactured and controlled at the atomic scale.

The significance of this for Australia should not be underestimated. Today, there is an international race to build a quantum computer and the field is highly competitive — nicknamed the space race of the computing era. There are currently four fast-moving potential implementations for making this work: one based upon superconducting circuits; one based on ion traps; one

[1] https://newsroom.unsw.edu.au/news/science-tech/seeing-believing-precision-atom-qubits-achieve-milestone

based upon a theoretical proposal involving rare sub-atomic particles called the Majorana fermions; and one based in the industrial-compatible silicon material. We are the world leaders in the last area, where Australia has established a unique approach with a globally competitive edge that has been described by our US funding agencies as having a two- to three-year lead over the rest of the world.

It is nail biting, it's exciting and it's happening here right now in Sydney. But what really inspires me now is that we are at the threshold of making this into something practical and real, with a demonstrable benefit.

Over the past three years, we have established a unique government/industry/university consortium with the focused aim of building a 10-qubit prototype quantum computer right here in Australia. It's not going to be easy. Technologically and scientifically, we face a new set of challenges as we scale up. I am acutely conscious too that getting these types of inter-sectoral undertakings off the ground is very difficult — more difficult, in fact, than some of the scientific challenges in quantum physics that I've faced in my career! To take things to the next level, we need to work across different cultures, where goals and expectations may sometimes be at odds.

Yet strangely, in this country, as in other parts of the world, we tend to institutionalise our researchers and to blinker them to the advantages and skills of their colleagues in other sectors. Thus, in the academic world, it is surprisingly common for people to disparage the profit motive and the private sector; while, in the commercial world, one often hears people denigrating the ivory-tower mentality of academics. And between both groups, I think governments sometimes struggle to understand either side of this equation. Yet parties fulfil important but different roles in our society, and play complementary parts in making new discoveries and in developing them into products or services of value to society. Sometimes we need to work together.

Given the importance of quantum information for the finance, health, transportation and logistics industries, and for the computing and communications industries, it is natural for Australian industry to begin to invest in this area. And in this regard, I have had the great fortune to work with outstanding trailblazers in some of Australia's leading high-technology companies, including the Commonwealth Bank and Telstra — an experience that has transformed my view of Australia's technological prowess in the commercial sphere. I am serious — if anyone can help us to make it happen, it is these guys. The technology leaders at these organisations are sharp, on the ball, an absolute delight to work with and at the very top of their game.

To do what we are planning we will all need to be. Quantum physics is hard. Technology at the forefront of human endeavour is hard. But that is what makes it worth it. I strongly believe that the things that are most worth doing in life are nearly always hard to do.

Which brings me back to the beginning, and to the fundamental lessons I learnt as a child. When I was growing up in England, before I became an Australian, I always knew that I liked doing things that were difficult — things that you had to try really hard to succeed at but that, when you did, the euphoria was immense. It is interesting, therefore, to admit now that I actually gave up physics at O Level as I also really enjoyed biology, chemistry, history and English literature. (Career advice at the time encouraged people to follow the subjects they enjoyed the most.) Shortly into my O Level year, however, I knew I had made an awful mistake. While I enjoyed these subjects, they didn't challenge me. I realised then that my greatest joy was solving problems that were complex and not so instantly rewarding to do.

The consequence for me was I ended up doing physics outside of school, and it took me a while to catch up. The lesson I learnt was you can always do the things you enjoy and find easy outside of work. But problem solving and technical skills require consistent effort and are not so easy to pick up at any time in life. For me, it was better to do the things that have the greatest reward. Things that are hard, not easy. And things that will continue to challenge you throughout your life.

Now, there's a message here for our educators, our scientists and for all Australians. First, science education.

Great teachers with high expectations challenge their students to be the best they can be. But equally important are the curricula that they teach. One of the few things that horrified me when I arrived in Australia was to discover that, several years ago, the high school physics curriculum was "feminised." In other words, to make it more appealing to girls, our curricula designers in the bureaucracy substituted formulæ with essays! What a disaster. From the students coming to university, I see little evidence that this has made any difference and indeed I see many students complaining that the physics curriculum has left them ill equipped for university.

In my experience, there is a big cost in this type of thinking. When we reduce the quality of education that anyone receives, we reduce the expectations we have of them. If we want young people to be the best they can be (at anything) we must set the bar high and tell them we expect them to jump over it. My strong belief is that we need to be teaching all students -— girls and boys — to have high expectations of themselves.

What about our scientists?

Our country has established centres of excellence that are the envy of scientists across the globe, in areas like robotic vision, astronomy, big data, gravitational wave discovery, brain function, ageing and ecology. Collectively, these initiatives continue to attract brilliant people from all over the world — most of whom come, no doubt, with a shared sense of hope and excitement, just like the one I held, and still hold, for this place.

Remarkably, three of these centres of excellence are focused on quantum physics and related technologies — each with a particular presence here in NSW. Australia, for some reason, is disproportionately strong in quantum information science. And, with billions of dollars of investment going into this field across the world, our next challenge is to see whether we can benefit from our international lead, to try to translate that research into high-technology industries here in Australia.

Finally, there's a broader message for all Australians. In Australia, when praising ourselves, even on occasions like this one, we tend to emphasise the beauty of our natural environment, our great lifestyle, and the easy-going nature of our people. The lucky country. I think this is a mistake, because it doesn't acknowledge the hard work that people have done to be successful and it encourages us to shy away from difficult challenges. In short, I believe it will eventually stop us from being as ambitious as we might be.

Of course, ours is a country of great spirit and enormous promise — something that outsiders don't always appreciate. With our inherent scepticism towards dogma and our openness and collaborative spirit, Australians are natural discoverers. We are also problem-solvers who like to get things done. But is this enough?

As we take things to the next phase of trying to build a prototype quantum computer, I feel proud to be a part of the team that is going to make this happen. I am grateful for that Australian spirit to give things a go, and our enduring sense of possibility. In this, we have so much to be thankful for — and, more importantly, so much to look forward to. But there is room for improvement as well. In our innovation policies, in our education system, and in the ambitions of our scientists and discoverers, I want Australians above all to be known as people who do the hard things.

Thank you, and happy Australia Day.

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