Why Australia is betting it all on silicon
“Scientists investigate that which already is; engineers create that which has never been.”

ALBERT EINSTEIN (1879–1955)
MAKING AN IMPACT

UNSW is pushing the frontiers of innovation with research that has the potential to reap enormous benefits for society.

LIKE MANY OF the world’s best universities, UNSW sits at the heart of a sophisticated global knowledge system shaping our future. Key to that mission is to translate research into real world solutions. That’s where engineering excels.

With more than 500 academics and researchers supported by 300 professional and technical staff, and expertise across nine schools and more than 40 research centres, we are the powerhouse of engineering research in Australia.

UNSW invests more than A$100 million a year in engineering research. And we are internationally renowned for our innovations in: energy, water, biomedical implants (such as the bionic eye), cybersecurity, transport, sustainable mining, food science, chemical engineering and nanotechnology – the list goes on. We work at the frontline of innovation.

This inaugural issue of INGENUITY profiles some of that work.

Like the global boom in solar power, ignited by work at our School of Photovoltaic and Renewable Energy Engineering, whose legendary Martin Green has made many advances in his 40 years at UNSW (page 32). And he has spawned an army of PhD students who have upended the field, including Shi Zhengrong, who founded China’s Suntech Power in 2001 and become the world’s first ‘solar billionaire’.

Similarly with water filtration, Chris Fell at our School of Chemical Engineering developed transformational membrane technologies using hollow nylon fibres that allowed macromolecules and pathogens to be removed from water at low pressures. That technology is today global, and every time you turn on a tap for a glass of clean drinking water, chances are it’s been treated using UNSW’s membrane filtration technology.

More recently, we’ve helped capture an unparalleled lead in one of the hottest, most competitive frontiers of innovation today: quantum computing. A universal quantum computer could, in theory, run millions of times faster than the fastest conventional computer, be commercialised and reap enormous benefits to society.

That global high ground is held by a bevy of remarkable researchers at UNSW who have devised unique approaches to creating silicon ‘qubits’ (or quantum bits) with the potential to be mass-produced: our Faculty’s Andrew Dzurak and Andrea Morello, and the Faculty of Science’s Michelle Simmons and Sven Rogge (page 22).

Doing excellent research is one thing, but just as important is to partner with industry and government, to ensure that the discoveries we make go on to deliver social and economic benefits for all.

Our research, as well as our graduates and the ideas and enthusiasm they take into the world, are our greatest contribution to society – something UNSW is determined to expand and enhance upon as part of its 2025 Strategy to make UNSW a global leader in discovery, innovation, impact, education and thought leadership.

We hope you will join us on this journey – as a supporter, partner, student or interested observer. The world faces many challenges in the decades ahead, but with determination and ingenuity, I believe we can solve many of them. We’ll certainly be doing our part.

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“The world faces many challenges ahead, but with ingenuity, we can solve many of them.”
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ELISSA KNOTHE TATE is equally comfortable with a microchip as a Petri dish. It’s the same for her research, which occupies the intersection between biophysics and cutting-edge engineering. “We intentionally go after the hardest research questions, which have gone unanswered because no current method exists to answer them. We develop new approaches and technologies to make the problem tenable.”

One of these new technologies made waves in 2015. “Our turbocharged electron microscope enables anyone to navigate and explore the ecosystem of the human body,” she says. Dubbed ‘Google Maps for the body’, the new imaging technique – originally developed by German high-tech manufacturer Zeiss to scan silicon wafers for defects – allows scientists to zoom in and out, from the scale of a whole joint down to a single cell.

The process uses similar algorithms as Google Maps to cope with the huge amount of data and stitch the images together into one zoomable picture. Not only does this offer unprecedented insight into how body processes work at different scales, but can also image areas as large as the human hip in hours – which would have previously taken decades.

The system cannot yet scan living patients, but is a launching point to investigating how large scale pathologies like joint failure relate to cellular health, says Knothe Tate. More recently, Knothe Tate has been applying her unique skills to weaving tissue patterns made by human cells. She optimises and scales the images using computer-aided design software to reveal the precise pattern of fibres of elastin (which makes tissues elastic) and collagen (which makes tissues tough) in tissues. The pattern is then entered into a 3D printing system or a computer-controlled, 19th-century wooden weaver’s loom that can weave up to 5,000 different threads independently.

Tissue patterns that offer strength, elasticity, smart responses and other advantageous properties can be applied to a host of different materials, including nylon, glass, titanium and silk. “The sky is the limit for multifunctional textiles made in this fashion,” says Knothe Tate. It opens the possibility for new fabrics, not only in the biomedical industry, but the transport and safety industries too. Her ultimate aim? To make tissue herself. “We recently had a breakthrough in engineering multicellular architectures using methods found in nature. Once we can form these templates, then the cells do the work of creating the proteins, which get secreted to form tissue.”

Melissa Knothe Tate: Unlocking the patterns of human tissue.
BIONIC VISION

UNSW’s Phoenix99 bionic eye is a fully implantable system that could restore vision in patients affected by retinitis pigmentosa and age-related macular degeneration. It’s a revolutionary technology that represents several world-firsts in both neural stimulation and the treatment of blindness.

STORY Gemma Conroy
ILLUSTRATION Jamie Tufrey

AT A GLANCE

- Retinitis pigmentosa affects around 2 million people worldwide. It is a leading cause of blindness in young people, often appearing when a patient is in their 30s.
- It is predicted that 196 million people worldwide will have age-related macular degeneration by 2020.
- Surgery to implant Phoenix99 takes a maximum of four hours.
- $10 million is needed over the next five years to continue developing the system.

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ARRAY

The first prototype, a partially implantable 24-electrode array, was tested on three patients in 2012. It enabled patients to see spots of light and perceive objects in the distance. After these encouraging results, a team led by UNSW engineers Nigel Lovell and Gregg Suaning collaborated with top surgical experts to develop the fully implantable Phoenix99 device, which contains a 99 electrode array. They hope to implant the device in a dozen patients within the next two years.

MICROCHIP

A digital camera transmits information as high-frequency radio signals to the microchip implanted in the retina. It works like a miniature radio station, but transmits signals through the skin rather than through wires.
GLASSES
The user wears a pair of glasses with a digital camera attached. This acts as a replacement for the damaged nerve cells in the retina.

ELECTRICAL IMPULSES
The 99 electrodes on the microchip convert the radio signals into electrical impulses which stimulate the healthy cells remaining in the retina. The impulses are passed down the optic nerve and interpreted as an image by the visual cortex of the brain.

CAMERA
The images taken by the camera help to define the stimulation of the nerve cells. Images are processed based on the most important features, such as how far away an object is.

PHONE
The images taken are processed by the user’s mobile phone, which can be connected to the camera with a cable or Bluetooth. The processed image is sent to the antenna behind the ear before being transmitted to the microchip.

TRANSMITTER
The only part of the implant system that can be seen is the lightweight antenna that sits behind the ear. It transmits data and power to the device implanted in the back of the eye.
The gathering storm

Studies of coastlines and cities, conducted in Australia with unparalleled sensitivity, are set to rewrite the world’s climate models and civil engineering guidelines.

STORY Lauren Martin
PHOTOGRAPHY Grant Turner

Storm ready: (left to right) Christopher Drummond, Kristen Splinter, Mitchell Harley and Ian Turner.
A

T LEAST 600 times over the four years he was earning the ‘Dr’ before his name, Mitchell Harley methodically combed northern Sydney’s Narrabeen-Collaroy beach on Australia’s east coast. Back and forth, like a kid mowing a vast sandy lawn, Harley rode a tech-packed quadbike, collecting data, logging his position on the beach – on the planet – to within 15 millimetres. “I knew every grain of sand,” he jokes.

The 3.6-km arc of sand, stretching and shrinking with the seasons and the storms, is etched in his memory. In 2010, when Harley moved to Ferrara, Italy, for coastal engineering work, he could still picture Narrabeen Head rising in the north; the rocky cliffs to the south; seas reaching out to the eastern horizon; and westward, the line of beachfront homes facing the waves and surfing the ever-rising tide of coastal property values.

Narrabeen-Collaroy is Australia’s longest-running coastal monitoring program and one of few sites worldwide to have been measured over 40 years, starting with a handful of scientists in the 1970s with nothing but graduated poles and measuring tape. Their work has grown into a rich archive for UNSW’s Water Research Laboratory. The program won global renown in April 2016 when the data was published in the Nature journal Scientific Data. Unusually, the lab made the data freely available for anyone seeking to understand beach erosion and the impact of climate change on our coasts.

“Many coastal-monitoring measurements start and happen for a year or two, or at most five years,” says the lab’s director, Ian Turner, who oversees both its academic research team and high-end applied-research consulting group.

“But if you continue for long enough,” says Harley, one of Turner’s senior research associates at the lab, “you see all sorts of patterns that have never been seen before.”

Patterns in the Narrabeen-Collaroy data show that El Niño and La Niña cycles can intensify coastal hazards. Across the Pacific, we now expect changing storm patterns associated with extreme coastal flooding and erosion. This rich data set emphasises that sea-level rise is not the only factor in coastal vulnerability – the patterns of storm erosion, and their increasing impact at the coast, are becoming more apparent, too.

Patterns are an engineer’s bread and butter. And they are what led UNSW engineers Ashish Sharma and Conrad Wasko to look for changes in the way that rain falls, in an article published in Nature Geoscience (June 2015) and in Geophysical Research Letters (April 2016) with colleague Seth Westra from the University of Adelaide.

Any third-year engineering student learns to study rainfall’s temporal patterns – because the ‘when and where’ of downpours is crucial to design structures able to withstand flooding when it occurs.

“This is something nobody in the climate community knows about; it’s a very engineering-specific thing,” Sharma says. “The climate guys think about big-picture stuff – things that happen over continents, over years. We are talking about a storm that might last 15 or 20 minutes, and it can create a flood. That is what we need to consider to design a little spillway, a little culvert, the foundations, or the plinth level of a house.”

The ways in which rain falls in a warming climate’s increasingly intense storms seemed to Sharma an obvious area to investigate. So he and his team systematically gathered all the independent data meticulously collected at schools and post offices across the nation, some of it for 200 years. Because Australia is so vast, the data covers all of the world climate zones, save for polar ones.

Among the insights drawn from the data, Sharma explains, is that as the atmosphere warms, not only do storms become more intense, they get ‘peakier’. At its peak, rain falls faster and over smaller areas. You get intense downpours, in smaller windows of time and space.

“It was a very clear result; it wasn’t one of those wobbly messages that often come with research papers,” Sharma says. “It was black and white. Rising temperatures exacerbate damaging flooding.”

Sharma presented his results across North America and Europe throughout 2016. The research has implications not just for developed nations (Australia has already partly adjusted its national flood-planning guidelines as a result of the research), but also for cities like Jakarta, Mumbai and Karachi, places which will have more and more instances of floods, according to climate models. And they will likely be lethal.

A

S JUNE 2016 approached, Harley was back on the Narrabeen-Collaroy beach. The air was still; his nerves were alert: something extraordinary was going on. He readied the technology at the lab’s disposal: drones, jet skis and a twin-engine airplane loaded with the laser sensing technology LiDAR, plus the building-mounted cameras and lasers that were always taking thousands of photos every hour and scanning the beach four times a second, day and night.

In five decades of close observation, Narrabeen-Collaroy had not seen a storm like this.

Like all coastal engineers, those at UNSW’s Water Research Laboratory (WRL) work at the dynamic nexus of sand and sea. At Narrabeen-Collaroy, it’s also the location of some very expensive residential property.

On Monday, 30 May 2016, as happens every day, Harley collected the forecast from Australia’s national weather agency, the Bureau of Meteorology. Routine work; run it through the algorithms the lab had developed to predict storm impacts on the beach. Then the data for the coming Sunday – 5 June 2016 – came back. And it went off the charts.

Harley ran it again. Off the charts again.

It wasn’t just that the waves would be big. “It showed six-and-half-
metre waves to hit on Sunday – that’s reasonably big for our coast, but not massive,” Harley says. “The really concerning thing was the direction they were coming from.”

Generally, the March-August storms that hit this part of the Southern Hemisphere come from the south. Australians call them East Coast lows (akin to American Nor’easters). But this one looked to be hitting from east-northeast.

“I’d seen storms from that direction during my PhD that were a lot less intense, but I had been surprised how much damage even small storms did,” Harley says. “So imagine, twice as big, from that direction. I almost literally spat out my coffee.”

To make it a triple-threat, the storm would coincide with king tides. “Biggest of the year,” Harley says. “Water levels then are several tens of centimetres higher than usual, so the waves are already going to attack higher up the beach than they normally would.”

This potentially epic event was still days away. And the forecast would ebb and flow over the next 48 hours, along with Harley’s adrenaline.

The WRL team was aiming for something rare and precious in coastal-monitoring: accurate pre-storm data. All around the world, researchers collect copious data after a storm. But they rarely see storms coming in time to mobilise detailed recording immediately beforehand.

The comparison, however, is what is most telling. With careful measurements before and after a big storm, the team could accurately analyse the impact of storms and the resulting erosion and damage. They would be able to understand much more about how sand moves, and then accurately model and predict the impact of future storms, Turner says.

He tells the story of Albert Einstein warning his son off studying sedimentary transport because it was too complicated. Climate change, Turner laughs, only adds to the complexity.

“Sea levels are rising, and we should anticipate a shift in wave patterns,” Turner says. “Not necessarily bigger storms, not necessarily more storms, but storms from different directions.”
The team had been preparing for this one. Over recent years, they’d come up with the algorithms that triggered Harley’s initial alert. They had also put together detailed mobilisation procedures jointly with the state’s Office of Environment & Heritage, which suppled staff, jet skis and boats. These were about to be thoroughly tested.

“We had to develop our own internal storm-warning system,” Turner says, brandishing the laminated plan-on-a-page he carries everywhere, “because we had to get out onto the beach in the 48 hours before the storm to measure the data we really wanted.

“It wasn’t by chance that we were there.”

On Wednesday prior to the storm, the Pacific seas were, in Harley’s words, “like a mill pond”. The dead-calm conditions ensured the jet skis could go out to survey the sand to a depth of 20m, and Water Research Laboratory pilots could fly the lab’s drones overhead. The quadbikes, now in touch with 15 to 20 geostationary satellites, GPS-checked every aspect of the beach. A UNSW Aviation plane flew above with its mounted LiDAR, making three-dimensional scans of the whole area.

A disappointed local surfer asked Harley what all the activity was about.

“I said, ‘Looks like there’s going to be a massive storm on Sunday, so we’re doing measurements ahead of it.’ And he’s like, ‘Nah, mate, you’re wrong. You guys have got to ask the surfers. They know best.”

As the weekend neared, the lab forecast increasingly showed a major storm event. The last tool Turner decided to deploy was a sophisticated – and expensive – wave buoy. There was a good chance the storm would claim it. The buoy is capable of measuring every wave as it is about to hit the beach. They had to risk it, Turner decided. On Friday, a boat anchored the buoy 300m out to sea. They waited.

WHEN THE STORM hit on Sunday, the impact was dramatic, and the engineers captured it all – the science and the sensation. Global media relayed Harley’s social media posts – such as “About six houses cracking up right now at #Collaroy with #kingtide. Grave conditions #SydneyStorm” – almost in real-time. Residents were evacuated, roads closed. A swimming pool slipped into the sea, building foundations fell, emergency services struggled with more than 10,000 requests for help. At Collaroy, more than half a dozen houses were severely damaged by the storm that left an estimated $56 million worth of damage in its wake. Worse, across Australia, at least five lives were lost to floods and wild surf.

The beach itself lost 50m in width. It was the largest erosion event recorded during Narrabeen-Collaroy’s 40-year monitoring program. Harley marvels that 12 million cubic metres of sand – “enough to fill the international Melbourne Cricket Ground stadium seven times, to the brim” – shifted during the storm.

The expensive buoy survived, and like the rest of the WRL tools, delivered much valuable information. “In future decades, what’s now a king tide will be an average high tide. And we’ll still have king tides,” Turner says. The storm came from an unusual direction, as did the waves, accounting for the severity of the overall damage. Relatively subtle changes. Huge impact.

“We are heavily focused now on being able to model and predict and indeed to forecast that type of event,” Turner says. Now they have the very precise data they need on which to base that kind of analysis. And with it, researchers around the world can begin to build vastly more accurate coastal erosion models, to predict damage days before a storm hits.

TURNING CARS INTO DEATH TRAPS

PEOPLE GET IN trouble in floods. Big trouble. “More people die in floods than in bushfires or earthquakes or tsunamis,” says Grantley Smith. “And most commonly when they are in a car or other vehicle.”

The manager and principal engineer of the UNSW Water Research Laboratory, Smith understands why drivers get into danger: “You feel pretty safe because you’re in something that weighs a tonne or more.”

Around the world, flood testing of cars has always used miniature models. So Smith decided to test the behaviour of actual vehicles in floods inside a huge, purpose-built tank. As the water rose, he found modern cars can float spectacularly easily. Even a child could push his parent’s SUV around the tank. With one finger.
The WRL team wants to build a national network of monitoring sites, to add to the insights from Narrabeen-Collaroy and other places. The lab has plans to develop and test a national coastal hazard and coastal erosion early-warning system, similar to those currently being developed in the USA and Europe, to identify and predict likely storm-affected areas down to a few metropolitan blocks, or whether the northern, middle or southern end of a beach will be hit the hardest.

There are still many questions.
“Where do we need to focus our resources? Where do we need to evacuate people? Where do we need to sand-bag?” says Turner.

WRL engineers are also in long-term planning discussions about the value of seawalls, sand nourishment and other buffer zones, or of beachfront-property acquisition and restoration. They’re helping raise and answer critical questions about how we protect infrastructure like arterial roads, ports, harbours and oil refineries.

“Now climate change is an important part of the picture, how do we adapt and modify as the opportunities arise?” Turner says. “Populations are increasing, and our infrastructure is increasing – we have to come up with solutions.”

The most dangerous thing you can do in a flood is drive your car into floodwaters,” Smith says. “These days, because cars are air-conditioned and electronic, they are airtight, dustproof and quite watertight as well. Even if you are in a large vehicle like a 4WD, once you’re in water, fundamentally you’re in a balloon.

There may be two tonnes of car, but there’s 6m³ of air in the cabin. If you’re in enough water, it would take about 6 tonnes of weight on top of the car to keep it on the ground.”

Smith says that over the past 15 years, as more SUVs take to the roads, the number of people dying in floods in vehicles has increased. “You’d think a heap of testing would have been done to find out what’s going on.” Smith says. Wrong.

Smith’s engineers take briefs from industry as well as initiating their own research in UNSW’s hydraulic laboratories, equipped with many custom-built experiments and a 44m wave flume, the largest in the Asia-Pacific region. Since WRL’s dramatic car testing results, Australia’s emergency services and insurers have waged continuous public-awareness campaigns about the dangers of driving in floods. The message? Just don’t do it.

– Lauren Martin

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An international project to study Earth’s poorly understood thermosphere uses a swarm of satellites – two of which were built at UNSW.

ON’T BE FOOLED by the diminutive size of the UNSW-EC0 cubesat. This 1.8kg box may be small, but the team who built it have high ambitions.

The miniature satellite is part of the European-led QB50 mission to explore Earth’s least understood atmospheric layer: the thermosphere. Built by a team at Sydney’s Australian Centre for Space Engineering Research (ACSER), the satellite was deployed, along with a constellation of 35 other cubesats, from the International Space Station in June 2017.

The thermosphere, between 200 and 380km above Earth, is a region vital for communications and weather formation and helps shield Earth from radiation from the Sun and harsh cosmic rays – a region where temperatures can hit 2,500°C (4,500°F). It’s here auroras form their flickering curtains of light, and where ultraviolet and X-ray radiation from the Sun can cause potentially catastrophic solar storms that can knock out power grids and communications. Yet until now, the region has been largely uncharted.

The objective of the QB50 project, led by Belgium’s Von Karman Institute for Fluid Dynamics and involving 28 nations, is to understand the atomic composition of this region. UNSW-EC0 carries a miniaturised ion
EYES ON THE SKY

THREE AUSTRALIAN CUBESATS were built for the QB50 project, two of them at ACSER, and they are the first satellites made locally in 15 years. But there are likely to be many more. "It’s an example of the philosophy behind ‘Space 2.0’, where the big expensive agency-driven satellites are being replaced by disruptive low-cost access to space,” says Andrew Dempster, Director of ACSER.

Its other QB50 cubesat was INSPIRE-2, developed jointly with the University of Sydney and Canberra’s Australian National University. This cubesat will measure the plasma density and electron temperature in the thermosphere.

"The QB50 mission is an opportunity to show what we can do at ACSER," adds Dempster.

ACSER is also a partner in Biarri, a cubesat mission for the Five Eyes intelligence alliance of Australia, New Zealand, Canada, the UK and the USA, to explore cubesat formation flying, verify the performance of UNSW’s Namuru GPS receivers and improve electro-optic systems used for precision orbital tracking.

And ACSER is a global leader in the emerging field of off-Earth mining, holding annual forums at which international participants explore how to mine space for water and minerals. It has constructed risk-based financial and technical models to evaluate multiple space-borne mining scenarios, and developed optimised mining systems to extract water on Mars.

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MAGINE A SOCCER grand final where a team of fully autonomous humanoid robots beats the latest winners of the World Cup, all within the official guidelines of FIFA.

This is the long-term vision for RoboCup, an international robot soccer championship that highlights the latest developments in artificial intelligence (AI) and robotics research.

Since first entering RoboCup in 1999, UNSW’s team rUNSWift has been a consistent leader in the competition. The team, made up of a mix of the university’s top engineering students...
It’s this ability to respond quickly that has set rUNSWift apart from other teams competing for the world title. Over hours of simulations and machine learning tests, the UNSW squad has developed a walking code that enables the robots to walk faster than most of their competitors.

“We start by designing the larger components, and then work our way down to the details of how each component will operate,” says Harris, who now creates software for Cruise GM’s self-driving cars. “We test several different approaches on a weekly basis and fine-tune the best for each task.”

RoboCup winners cannot rest on their laurels. Each year, the software developed by the winning team is shared with all other teams, forcing the technology to accelerate to stay ahead.

RoboCup attracts interested scouts from leading technology brands, such as Google, Microsoft and Dell. It will be held in Sydney in 2019 and is expected to attract up to 600 teams and 20,000 spectators.

and robotics experts, has taken out five world titles, most recently in 2014 and 2015. Only one other team, Germany’s B-Human (a joint team from the University of Bremen and the German Research Centre for Artificial Intelligence, or DFKI) have managed to equal them.

“This is the ‘space race’ of robotics,” says Maurice Pagnucco, Deputy Dean (Education) of UNSW’s Faculty of Engineering and Head of the School of Computer Science and Engineering. “What we learn from robots playing soccer can be applied to industry and help us solve difficult, real-world problems.”

The competition is a standard platform league of fully autonomous Nao humanoid robots, which compete against each other in teams of five. With no physical advantage, what differentiates the teams from each other is the software and AI the engineers create in the months leading up to the competition. Once the game kicks off, the robots are on their own.

“The design process is challenging, as we have to create software that’s robust enough to handle the different situations a soccer player may face,” says software engineer Sean Harris, rUNSWift’s successful leader in 2014 and 2015. “The robot must react quickly and effectively in a variety of unknown situations.”
There are two million near-Earth asteroids in our Solar System, containing vast mineral resources, and, even more vitally, water. Plans to survey them are already underway.

ASTROLOGY
Robin McKie
PHOTOGRAPHY
Quentin Jones

JUST THREE KILOMETRES in diameter, asteroid 1986DA is a fairly tiny affair by astronomical standards. Yet it contains astonishing wealth. Using radar, astronomers have discovered 1986DA is mainly made up of iron and nickel.

“Essentially, it is a ball of naturally occurring stainless steel,” says Serkan Saydam, a UNSW expert on the mining of off-Earth objects.

Asteroid 1986DA is also estimated to contain more than 10,000 tonnes of gold and 100,000 tonnes of platinum.

The prospect of such mineral riches excites some entrepreneurs. These visionaries picture a fleet of robot spaceships crossing the Solar System to mine its interplanetary resources. This would also open worlds like the Moon and Mars to human colonisation.

With its vast mining experience, Australia is keen to ensure it is in the vanguard of these operations. Hence the appointment of Saydam as an associate professor of mining at UNSW, where he is putting together a small team of off-Earth mining experts. The work of Saydam’s honours student Georgia Craig on asteroid 1986DA highlights the importance of the careful planning that will be needed in future — and the problems that lie ahead.

NAMED AFTER THE year in which it was discovered, asteroid 1986DA orbits the Sun 75 million
Planetary prospector: Serkan Saydam’s team is helping NASA’s Jet Propulsion Laboratory to mine water on Mars.
kilometres from Earth and is rated by
the International Astronomical Union
as a Near Earth Object, or NEO. But
calculations by Saydam show that
1986DA is still too remote to be mined
economically. On the other hand, his
research suggests that if the asteroid
were half its current distance from
Earth, it could be viable to exploit.

That is good news because there are about two million other near-Earth asteroids orbiting the Sun. If we can find a better-placed candidate, it could become a target for mining operations. Hence the activities of companies like Planetary Resources (see ‘Frontier horizon’, above) which is preparing to carry out detailed surveys of NEOs to find one best suited for mining operations.

Asteroids like 1986DA are not the only targets for future missions. Other types of asteroids contain far less mineral wealth, but much more water. That could be crucial, says Saydam.

“Water will be our prime source of fuel in space, and finding sources will be a priority. Hydrolysis of water produces hydrogen and oxygen, which can be burned together as fuel, and used in space shuttles and/or satellites. To put it bluntly: water is going to be the currency of space.”

Worlds like Jupiter’s moon Europa, which has a vast ocean below its frozen surface, and Saturn’s tiny Enceladus, which vents water into space, would be good targets but are too remote.

“We will have to find water much nearer to home, and given that we have to start somewhere, Mars is the logical place to begin our hunt for water on another world,” says Sophia Casanova, a geologist and PhD candidate who is now studying off-Earth mining at UNSW. “Finding and extracting water will be crucial for setting up colonies there.”

The trouble is that, while the poles of Mars have ice, they are too cold and inhospitable to provide homes for early colonists. By contrast, Mars’s equatorial region is warmer and more amenable but lacks water – at least on the surface.

“That means we will have to seek it underground,” says Casanova, whose research is now focused on finding ways to pinpoint rich deposits of clays and hydrate deposits at lower latitudes on Mars. “There could be some kind of artesian wells, but we have no evidence of their existence as yet. So we will probably have to use hydrate minerals.”

But how can we extract water from rocks? Casanova explains: “You could put your minerals in a chamber and heat them to extract the water. Alternatively, you could use microwave generators that heat the underground
to break up the rocks and release the water that way.”

At NASA’s Jet Propulsion Laboratory in California, Saydam’s team has developed models to evaluate multiple off-Earth mining scenarios (See ‘Water on Mars’, right).

A NOTHER PRACTICAL PROBLEM concerns the use of seismic detectors. On Earth, a charge is set off and seismic waves that bounce off subterranean deposits reveal their presence. But as a tool for exploring other worlds, the technique is poorly developed. “Some seismic measurements were taken of the Moon by Apollo astronauts, and that’s about it,” says Michael Dello-Iacovo, a former geophysicist and now a PhD candidate at UNSW. “An early Mars lander was designed to do that but crashed. Now the Mars InSight Mission is being prepared to carry out seismic studies but will not be launched until 2018.”

Seismic waves may behave very differently on asteroids or other planets, says Dello-Iacovo. “There will be no atmosphere, and virtually no gravity, and we have no idea how that will affect seismic wave behaviours. My research is aimed at tackling that problem,” adds Dello-Iacovo, who is spending a year at JPL working on methods for improving our understanding of asteroid interiors. “We still don’t know if asteroids have solid cores or are just piles of rubble held together loosely,” Dello-Iacovo says. “If the latter, they might break apart if only a small force is applied to them during a mining operation.”

A host of ethical and legal issues also need to be overcome, says Saydam. “What treaties are we going to have to set up to exploit space? And what would happen if we suddenly turned a rare metal like platinum into a commonplace one by bringing huge chunks back to Earth? We could trigger a crash in international metal markets.”

“On the other hand, off-Earth mining has the potential to trigger great expansion in the global economy and we must make sure that Australia can influence that through its research capabilities. We also need to make sure we have trained manpower to take advantage of this great adventure.”

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FROZEN, CRACKED AND flowing in salty brines down the sides of steep crater walls, the Red Planet has revealed itself as a veritable reservoir of water. In fact, scientists from NASA and the University of Texas, Austin, estimated the Utopia Planitia region in Mars’s mid-northern latitudes holds as much as 12,000 cubic kilometres of water – the same as North America’s Lake Superior.

Serkan Saydam, with colleagues Andrew Dempster, from the Australian Centre for Space Engineering Research, and Jeff Coulton from UNSW Business School, are collaborating with NASA’s Jet Propulsion Laboratory (JPL) and Kennedy Space Centre (KSC) to work out what it would take to tap into this water wealth.

For future astronauts facing yet more recycled urine for their midmorning coffee, access to water on tap could be a game-changer for a long-lasting human presence on Mars.

“The aim of the research with JPL is to develop an integrated set of risk-based financial and technical models to evaluate multiple off-Earth mining scenarios to support a Mars colony,” says Saydam.

With PhD student Carlos Tapia Cortez, they simulated, optimised and assessed the performance of various Martian mining operations.

“We have identified combinations of market variables, technical parameters, and policy levers that will enable the expansion of the global economy into the Solar System and return economic benefits,” says Saydam.

The Water Extraction Mars Mining Model is currently being used at JPL, while the UNSW team is now working with KSC, Virginia Tech and Ascentech to further develop this model for a future manned landing.

- Heather Catchpole
Andrew Dzurak (left) and Andrea Morello outside clean rooms at the UNSW node of the Australian National Fabrication Facility. Behind them are PhD student Ruichen Zhao and postdocs Tuomo Tamtsu and Kok Wai Chan, dressed to avoid contamination of sensitive silicon nanoscale devices.
In the space race of the 21st century, Australia is betting it all on a key group of researchers and their elegant designs for a silicon quantum computer.

STORY Wilson da Silva  PHOTOGRAPHY Quentin Jones
ANDREA MORELLO is not what you expect when you think of quantum computing. Tall, lizard-thin and sporting a luxuriant ponytail and greying goat-patch beneath his lower lip, in skin-tight pants and a pendant, he has an intense gaze that could almost hold you in a trance.

“There were no silicon qubits before we started working on this,” says Morello, winner of the American Physical Society’s inaugural Rolf Landauer and Charles H. Bennett Award in quantum computing in 2017 for work some deemed almost impossible. “We’ve really contributed to making it work, and it’s now created a field. And we’re in the lead.”

In this, Morello is part of a two-man act. His friend and one-time mentor, Andrew Dzurak, who has been working on silicon quantum computing concepts since 1998, hired the young Italian postdoctoral fellow from the University of British Columbia in Canada – where he’d been working at TRIUMF, the venerable national physics laboratory. Morello joined Dzurak in 2006 as a senior research associate at what eventually became UNSW’s Centre for Quantum Computation and Communication Technology (CQC2T).

The challenge? To build on UNSW’s promising work on solid-state quantum devices, utilising the fuzzy superpositioned data that is a feature of quantum computers – known as quantum bits, or ‘qubits’ – and develop techniques for quantum control of single atoms in silicon.

A decade later, the duo are in the hot seat of what has been called the ‘space race of the century’: the global effort to build super-powerful quantum computers that could solve problems beyond the practical reach of even today’s best computers, like integer factorisation or the simulation of quantum many-body systems. And at CQC2T, the duo are key players in the world’s largest collaboration working to create a complete ecosystem for universal quantum computing.

Unlike almost every other major group elsewhere, CQC2T’s quantum computing effort is obsessively focused on creating solid-state devices in silicon, the heart of the US$380 billion global semiconductor industry that makes all of the world’s computer chips. And they’re not just creating ornate designs to show off how many qubits can be packed together, but aiming to build qubits that could one day be easily fabricated – and scaled up to the thousands, millions and billions.

“The infrastructure you need to make the kind of silicon qubit devices we build is unheard of in a university environment,” says Morello. “There’s basically no one else in a university setting that has access to these sort of advanced facilities.”

Dzurak, bespectacled and with a mop of tousled hair and a penchant for sharp jackets, is the man who makes that infrastructure possible. After a PhD at the University of Cambridge, where he had been working on gallium arsenide quantum dots to investigate fundamental physics phenomena, he joined UNSW in 1994 to establish Australia’s highest resolution electron-beam lithography capability, building devices as small as 10 nanometres.

He then became one of the architects of the UNSW node of the Australian National Fabrication Facility, an advanced nanoscale manufacturing hub with a complete silicon metal-oxide-semiconductor process line – the precise infrastructure needed to make silicon qubit devices, and he now serves as director of UNSW’s 750m² facility.

“The complexity of the infrastructure necessary to fabricate at that scale and with that level of precision is only found in billion-dollar factories where silicon integrated circuits are made,” says Dzurak. “Our goal is to develop, and demonstrate, the science and engineering of building a 10 qubit silicon device within five years. Ideally, you want to get to 10 qubits using a method that doesn’t substantially deviate from the way that a billion transistors are put on a chip.”

Morello adds: “If you can do that, then you’ve hit the jackpot, because we would then know how to make a qubit chip at scale and sell it at an affordable price.”

Dzurak agrees: “A big challenge is to actually get near 10 qubits. Once you get to that scale, the pathway forward becomes much clearer. Once we have shown the scientific and technical basis for 10 qubits, then our aim is to prove that you can use it to make 100, or 1,000 or 10,000.”

The heart of a modern computer is the microprocessor, or CPU (central processing unit), a complete computation engine on a single chip. Information is represented by bits, a binary code (yes/no, on/off) which is always either a 0 or a 1. Each of the 0s or 1s is called a ‘binary digit’, or bit, the core of the binary code that drives today’s computers.

This binary code is translated into instructions, which create everything from large calculations to luscious graphics on a screen. While computers...
these days are extremely fast, the mathematics of binary operations have limits – they still require calculations to be one after another, in a serial fashion, essentially in the same way as by hand. Even when multiple CPUs break down this task, such as in parallel processing, they still do it sequentially.

Computers cannot defy the mathematics of binary operations; all they can do is make those calculations faster and faster, by increasing the number of transistors on a chip, and making the transistors so small and responsive that they can switch over a billion times per second. Which is why modern chips pack hundreds of millions of transistors on a silicon chip the size of a fingernail.

Binary code is processed in circuits called logic gates, made from a number of transistors strung together. Logic gates compare patterns of bits, and turn them into new patterns of bits, with the output from one gate feeding the input of the next, and so on. If done in a human brain, this would be called ‘addition’, ‘subtraction’ or ‘multiplication’.

A quantum computer exponentially expands the vocabulary of binary code words by using two spooky principles of quantum physics, namely ‘entanglement’ and ‘superposition’. Qubits can store a 0, a 1, or an arbitrary combination of 0 and 1 at the same time. Multiple qubits can be made in superposition states that have strictly no classical analogue, but constitute legitimate digital code in a quantum computer.

And just as a quantum computer can store multiple values at once, so it can process them simultaneously. Instead of working in series, it can work in parallel, doing multiple operations at once. Only when you try to interrogate what state the calculation is in at any given moment – by measuring it – does this

“They’re aiming to build qubits that could one day be easily fabricated – and scaled up to the thousands, millions and billions.”

Ohio State University

ISSUE ONE WINTER 2017
A number of options exist. Dopant atoms such as phosphorus or arsenic can be added to a silicon crystal; either the spin of the dopant atom’s nucleus or that of the electrons in orbit around it, are used to create qubits. The nuclear spin approach holds the record in the solid state for a longevity of 30 seconds. Similar spin qubits can also be made artificially, using electrodes and semiconductor structures to trap electrons inside quantum dots. Silicon, purified of all its isotopes except for one, helps boost the stability of qubits. It also has the advantage of using the tools and infrastructure of the existing global computer industry. The small size of quantum dots and attendant systems makes interconnects challenging, but also allows a small footprint even when integrating a huge number of qubits. While scalable architectures exist on paper, they have yet to be demonstrated.

COMPANIES
Intel, HRL

RESEARCH LEADERS
UNSW, University of Wisconsin-Madison, TU Delft, Princeton, Sandia National Labs, RIKEN

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Dzurak’s team modifies silicon transistors to make quantum dots, or ‘artificial atoms’. A metal electrode attracts one electron underneath it, and its spin encodes the qubit. These can be strung together to create entangled qubit arrays.

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Morello’s team encodes quantum data into the spin of phosphorus atoms, inserted into the silicon chip in an industry-standard process. They then build electrodes and transistors around the atoms to control their quantum state.

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Simmons’s team creates precision atomic-scale transistors where each atom naturally hosts the spin qubit and can be uniquely engineered to form large arrays for error-corrected quantum computing processors.

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How fast is that? One way to measure the processing speed of computers is to calculate their number of ‘flops’, or Floating-point Operations per Second. Today’s typical desktop computers run at gigaflops (billions of flops, or 10^9). By comparison, the world’s fastest supercomputer, China’s Sunway
TaihuLight, runs at 93 petaflops (93 quadrillion flops, or around $10^{15}$) – but it relies on 10 million processing cores and uses massive amounts of energy.

In contrast, even a small 30-qubit universal quantum computer could, theoretically, run at the equivalent of a classical computer operating at 10 teraflops (10 trillion flops, or $10^{13}$), according to David Deutsch, at the University of Oxford’s Centre for Quantum Computation.

Granted, quantum computers are not measured in flops – in fact, they just don’t operate like the computers we’ve come to know at all. But it’s this promise of extraordinary processing power, plus the fact we’re reaching the limits of what can be done with classical computers, that make them such an intoxicating prospect.

**DIAMOND VACANCIES**

| LONGEVITY | 2 seconds |
| NUMBER ENTANGLED | 2 |

Atomic defects in diamond are used, and a nitrogen atom occupies a position near the vacant site in the lattice. Three qubit types can be made: one from the combined spin of multiple electrons attracted to the nitrogen atom, or by using the spin of the nitrogen atom’s nucleus, or of a nearby silicon nucleus. Diamond qubits are attractive as they interact with visible light, potentially enabling long-range communication and entanglement, and may stay stable enough for computation up to room temperature. Precise placement of the nitrogen atoms is a challenge, and may be an obstacle to fabricating large qubit arrays. Up to six spins have been entangled by coupling an electron with nearby random silicon nuclei near a vacancy, although this is not an ‘extendible’ set of six qubits, the extendible number is two. Entanglement has been achieved with two defects in distinct diamond crystals separated by as much as 13 km.

**COMPANIES**

Quantum Diamond Technologies

**RESEARCH LEADERS**

TU Delft, University of Stuttgart, University of Chicago, Harvard University, USTC Hefei

**TOPOLOGICAL QUBITS**

| LONGEVITY | untested |
| NUMBER ENTANGLED | none to date |

Topological qubits are based on non-abelian anyons, quasi-particles that emerge from the interactions inside matter, travelling at the boundary between two different materials. Their quantum states are encoded in the different braiding paths they follow in time. Because the shapes of the braided paths lead to the qubit superpositions, they would be ‘topologically protected’ from collapse, similar to how a shoelace stays tied even if it’s bumped. In theory, a topological quantum computer wouldn’t need to devote so many qubits to error correction. However, this topological protection only holds when the total charge in the system is conserved, which requires extremely low temperatures and highly controlled electromagnetic environments.

**COMPANIES**

Microsoft, Bell Labs

**RESEARCH LEADERS**

TU Delft, Niels Bohr Institute

The big players in quantum computing research are the UK, Australia, Canada and the USA, according to Ned Allen, chief scientist at Lockheed Martin in Bethesda, Maryland, USA. But there are many more rookies playing hard to catch up: “There are significant investments being made in Russia and practically every other developed country,” says Tim Polk, former assistant director of cybersecurity at the White House’s Office of Science and Technology Policy.

It’s not just computing; the unique properties of the quantum world are also revolutionising everything from sensing, measurement and imaging, to navigation and communications, with a plethora of useful applications in healthcare, defence, oil and gas discovery, flood prevention, civil engineering, aerospace and transport.

It’s being called the Second Quantum Revolution: the first rewrote the rules that govern physical reality, while the second takes those rules and uses them to develop new technologies.

The UK is investing US$76 million a year in quantum technologies, the USA some US$260 million, China US$158 million and Germany US$90 million, according to a UK Government Office for Science report. Another by consulting firm McKinsey estimated that, in 2015, there were 7,000 people working in quantum technology research worldwide, with a combined budget of US$1.5 billion.

However, it’s in quantum computing where the race is fiercest. Tech giants Intel, Microsoft, IBM and Google are all ploughing tens of millions of dollars, mostly betting on different horses – or, like Intel, on a few (see ‘Designs for a universal quantum computer’, at left).

Because the need for the faster calculations promised by quantum computing are so urgent, and the potential payoff so large, some have settled on an interim solution: an ‘adiabatic’ quantum processor that can solve specific problems, such as finding the global minimum value of a highly complex function. A nifty example of this approach was developed by Canada’s D-Wave Systems, which uses a kind of quantum tunnelling, coupled with binary inputs from classical computers, to develop a near-range solution to complex calculations.

But D-Wave’s computers don’t always provide the most efficient, exact solution; and while rapid, they are not always faster than a classical supercomputer. The quantum states of its qubits are more fragile, and their manipulation less precise – all of which narrows its usefulness to optimisation problems that need to be solved fast but don’t need to be perfect, such as pattern recognition and anomaly detection. Which is why Google and Lockheed Martin have each bought one of the US$10 million machines.

Nevertheless, D-Wave’s design doesn’t have the flexibility in the interaction between qubits to be a truly universal quantum computer – one that can perform a broad range of computations...
much faster than a classical computer; in some cases, exponentially faster. And that’s the holy grail.

This race, however, is still wide open, with competing technologies in play, all exploring different approaches to achieve the same goal.

Dzurak was recruited to UNSW by Bob Clark, a former Australian Navy officer and one-time chief defence scientist who is considered a visionary and one of the few Australians bestowed with a US Secretary of Defense Medal. Clark joined the navy at 15, rose to lieutenant, then left to complete a PhD in physics at UNSW and later at the University of Oxford, where he ended up heading a research group in experimental quantum physics at the famed Clarendon Laboratory, before returning to his alma mater in 1991.

At UNSW, Clark founded the centre that is now CQC2T, pushing for the creation of nanofabrication facilities. In 1997, Bruce Kane, then a senior research associate at UNSW, hit upon a new architecture that could make a silicon-based quantum computer a reality. His colleagues were enthralled, and Clark pressed Kane to develop the idea, and patent it. Kane’s 1998 Nature paper has now been cited over 2,500 times.

Kane’s paper also sparked the interest of Michelle Simmons, then a research fellow at the University of Cambridge’s renowned Cavendish Laboratory who’d gained an international reputation for her work in quantum electronics. “I wanted to build something – something that could prove to be useful,” she recalls. Whereas in Britain, she worked “with pessimistic academics who will tell you a thousand reasons why your ideas will not work … Australia offered the freedom of independent fellowships and the ability to work on large-scale projects.”

She joined UNSW in 1999, became a founding member of CQC2T, and in 2010 took over as director. Simmons now leads the UNSW-based collaboration of more than 180 researchers across six Australian universities – UNSW, Melbourne, Queensland, Griffith, Sydney and the Australian National University – as well as Australia’s Defence Science and Technology Group and the Australian Signals Directorate.

International partners include the universities of Tokyo, Wisconsin-Madison, Purdue, Singapore National and Oxford, Germany’s Max Planck and Walter Schottky institutes, and corporate partners IBM Research, Toshiba, Zyvex and Quintessence.

Recently, the UNSW quantum computing effort – its funding renewed for another seven years – has attracted another A$70 million from the Australian government, the Commonwealth Bank of Australia and telecom giant Telstra to create a consortium that will commercialise the three unique architectures they have developed. Discussions underway with additional partners will likely take this sum to A$100 million.

“All groups are racing to achieve ‘quantum supremacy’, in which a quantum computer performs a calculation faster than any known computer could. While an important milestone, this alone will not determine the winner.”
than 150 scientific papers and he’s a co-inventor on 11 patents.

Morello’s team was the first to demonstrate the read-out and the control of the quantum state of a single electron and a single nuclear spin in silicon. In a 2014 paper in *Nature Nanotechnology*, they set the record for how long a quantum superposition state can be held in the solid state, exceeding 30 seconds – 10-fold better than before. This helped him, with just 50 scientific papers under his belt, to win the Landauer-Bennett Award in 2017, “for remarkable achievements in the experimental development of spin qubits in silicon”.

Simmons’s group has developed the world’s smallest transistors and the narrowest conducting wires in silicon made with atomic precision. In a 2015 *Science Advances* paper, her group – working with Lloyd Hollenberg at The University of Melbourne – outlined a complete architecture for an error-corrected quantum computer, using atomic-scale qubits aligned to control lines inside a 3D design.

Simmons has published over 400 papers, has her name on seven patents, and a slew of prizes, including the Foresight Institute’s 2016 Feynman Prize for her experimental work in atomic electronics. In 2017, she was in Paris to collect the L’Oréal-UNESCO For Women in Science Award.

Rogge works closely with Simmons’s team to help understand fundamental issues related to the qubit environment. In a 2013 *Nature* paper, Rogge’s team detailed how to couple a silicon qubit to photons for quantum interconnects, and in a 2016 *Nature Nanotechnology* paper – in collaboration with the universities of Melbourne and Purdue – showed how to pinpoint a phosphorus atom in silicon with absolute atomic accuracy.

“No one yet knows what qubit design will eventually power a universal quantum computer. Or what technological approach will create the most efficient universal quantum computer that can be scaled up, at a reasonable cost, to solve the curly problems beyond the ken of supercomputers today.

All groups are racing to achieve ‘quantum supremacy’, in which a quantum computer performs a calculation faster than any known computer could. While an important milestone, this alone will not determine the winner. That will take a decade – or more – to settle.

History is replete with examples where it’s not the best technology that gains a foothold, or the cheapest, or even the one that scales up fastest. Cars, light bulbs, video recorders, nuclear reactors – all have seen less than optimal designs rise to prominence. And occasionally, better designs make a comeback, like electric cars; or designs that were once thought to be in competition – like AC versus DC for electricity, or AM versus FM for radio – carve out their own niches.

It’s also possible quantum computing will not be like classical computing, with a ‘one size fits all’ approach winning out. And it will take a long time for a standard to emerge, as it did with today’s computers. It took four generations of computers to get from bulky vacuum tube circuitry and magnetic drum memory to the multi-core CPUs with silicon semiconductor logic gates common today.

It may be that some chip designs are very powerful for specific uses, whereas others will be more easily adapted to universal computations. In all cases, it’s unlikely quantum computers will grace desktops of the future: because they require specific environments – a vacuum and low temperatures – they will most likely be used via cloud-based computing access from central sites. “I’m passionate about it because we’ve got a chance,” says Dzurak. “And if we make it work, then it’s something that could change the world.”

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We often picture disease-causing bacteria as an invading army of individual cells. But in fact, these pathogens find strength in numbers, glomming onto each other and coating the surfaces around them in near-indestructible protective sheets called biofilms.

These biofilms pose an enormous problem in medicine. They can form directly on lungs, wounds or other living tissue, and can contaminate medical devices such as catheters, prosthetic joints and other implants. Food production, water treatment, and other industrial facilities can also fall victim to their powers. Many types of biofilms resist antibiotics, and the bacteria they’re built from churn out toxins that make their human hosts sick. Yet, no good way exists to destroy them.

Cyrille Boyer, a polymer chemist and Co-Director of the Australian Centre for Nanomedicine at UNSW in collaboration with Dr Nicolas Barraux, believes that a nanomaterial he designed – a polymer-coated iron oxide particle that heats up when a magnetic field is applied – can provide a solution. In December 2015, he and his colleagues reported in Nature’s open access journal Scientific Reports that using these nanoparticles to raise the temperature of a biofilm by just a few degrees caused it to break apart.

Solo-swimming bacteria are much more susceptible to antibiotics, Boyer explains, so the researchers could then send in another type of particle to deliver medicine that kills off the bugs. They are now planning on testing the particles in live mice and discussing a potential partnership with a company interested in taking the method into clinical development.

Polymer chemist Eva Harth from Vanderbilt University in Tennessee, describes it as an out-of-the-box strategy to treat a long-intractable problem.
“This paper shows that a polymer construct can be much more effective than a traditional drug,” she says.

“There’s an enormous need for new technologies” for breaking up biofilms, says Rodney Dolan, Director of the Biofilms Laboratory at the US Centers for Disease Control and Prevention. “It’s a very creative, very interesting approach, particularly combining particles with magnetic fields to localise and control the effect.”

BOYER IS A master of materials, and his specialty is controlling the effects of the nanoparticles and polymers he creates. “In my team, we are looking at how to make smarter nanoparticles, where the nanoparticle acts in response to an external signal,” he says. In 2015, Boyer was awarded the Australian Prime Minister’s Prizes for Science Malcolm McIntosh Prize for Physical Scientist of the Year for his work using light to catalyse the assembly of polymers with distinct properties. Although the biofilm-busting technique doesn’t employ light, it’s right in line with Boyer’s vision of building ‘smart’ particles whose behaviour can be controlled for therapeutic purposes.

Boyer created his iron oxide particles in response to a discovery made by microbiologist Nicolas Barraud at the Institut Pasteur in Paris, France. The two met by chance, when Barraud, then based at UNSW, was attending a conference out of town. He popped in on a talk Boyer was giving about polymers that release nitric oxide. “It was a serendipitous meeting,” he says. “We realised we were working at the same university, a few buildings across.”

Barraud was studying the basic properties of biofilm formation and dispersal, and had recently discovered that nitric oxide could break up biofilms. Back in Sydney, he asked Boyer if he could try the polymers described in the talk. Boyer was happy to comply, and the approach worked relatively well, according to both researchers. They published a couple of papers, filed a patent, and are still pursuing the project — but the drawback was that nitric oxide is a gas, which makes it difficult to spatially and temporally control its release.

Barraud had also discovered that giving biofilms a tiny temperature boost made the bacteria move and shake, ultimately disbanding them, but he couldn’t work out how to apply the discovery. Then one day, over a beer, Boyer mentioned that he could create particles that induce local heating. “I’ve worked with chemists before,” Barraud says, “and usually as soon as you get into the lab you run into problems. But with Cyrille’s polymer, it was very straightforward,” he says.

That’s because in this project and others, Boyer focuses on identifying simple, well-worked-out polymerisation methods that can be used in specific applications. “Very precise materials that are easy to make — that’s the key,” says Barraud. “It’s smart, easy, and elegant — that’s what he’s after.”

Left: Cyrille Boyer of UNSW’s School of Chemical Engineering. Below: Biofilm of Staphylococcus aureus (or ‘golden staph’) on a catheter; bloodstream infections with this bacteria kill 20 to 35% of patients within a year.

AT A RECENT conference, someone snapped a photo of Cyrille Boyer standing outside a building, and reflected in the window behind him. Colleagues joke that the photo answers a burning question many have about the young materials scientist: “Nobody really knows when he does all the research he does,” says Eva Harth, who met Boyer when he invited her to participate in a conference several years ago. “Maybe there are two Cyrilles!”

As a polymer chemist, Boyer decided to feed his concurrent interest in biology by seeking out biological applications for the molecules he was learning to build. He tackled his first biologically-inspired project less than a decade ago, working with Tom Davis at Monash University in Melbourne, Australia, to grow polymers from simple proteins. Since then, he has published more than 150 research papers and filed seven international patents. “He’s incredibly fast and creative,” says Harth. “I have no idea where this guy gets his energy from — it’s just incredible to watch.”

Over the past five years or so, research at the intersection of polymer chemistry and nanomedicine has exploded, as scientists discover new ways of synthesising and manipulating materials. By all accounts, Boyer is at the leading edge in this creative wave; in particular, a light-induced polymerisation technique he discovered a few years ago, is now well known and widely used. “It’s giving the entire field enormous stimulus,” says Harth.

These new approaches for generating nanomaterials equip researchers with the tools to develop innovative ways of fighting infections, delivering drugs, and otherwise interfering with disease mechanisms. “This type of technology is a big advantage, because you can control more accurately where in the body you’re acting,” says Boyer.

But his vision goes even further. Ultimately, Boyer hopes to create even ‘smarter materials’ that don’t need any type of external stimulus but simply respond to the signals available within the body — a detector that senses a drop in glucose levels, for example, coupled with a delivery system that rectifies the deficit. “It’s a natural evolution toward such an integrated system,” he says.

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notches in the scientists’ belts. The more sunlight solar cells can convert, the less manufacturing, transport, installation and wiring is needed to deliver each watt – moving solar energy closer and closer to knocking coal off its perch as the cheapest form of energy.

UNSW photovoltaics researchers, led by Martin Green – often dubbed the ‘father of photovoltaics’ – have held world records for efficiencies in solar cells in 30 of the past 33 years. And with its strong track record in research commercialisation, UNSW’s prototype technology is setting the trends for the commercial solar market. Meanwhile, their focus is on developing the next generation of solar cells – pushing forward to a zero-emission future.

Hao’s thin black tile had become the newest champion in the solar cell race: one of seven world records UNSW photovoltaics researchers broke in 2016. Efficiency records are not just

Led by the legendary Martin Green, UNSW’s photovoltaic researchers have toppled world records in solar cell design again and again, and ushered in a commercialisation boom around the world. But they ain’t done yet.

Laojing Hao couldn’t sleep. Two weeks earlier, the UNSW engineer had sent a thin black tile, barely the size of a fingernail, to the US for testing, and she was waiting anxiously for the results. Her PhD students were equally on edge.

It was midnight when Hao checked her email one more time. It was official: her team had broken a solar cell world efficiency record. “I was full of joy at the achievement,” Hao recalls. “I shared the good news with my team immediately – we made it!”

Hao moved to Sydney in 2004 from China, where the solar industry is booming. A materials engineer by training, Hao was intrigued by the frontline photovoltaic research on thin-film solar cells at UNSW.

These cells have benefits over the more traditional silicon cells. The manufacturing process doesn’t require high temperature steps. They can also be much thinner than bulky wafer silicon, and so could engender new solar applications: imagine solar-powered electric cars, building-integrated solar cells or photovoltaic glazing on windows.

So far, the thin-film uptake in the markets has been sluggish: commercial thin-film cells make up only around 8% of the solar market. The problem is that the commercial products available,
Cadmium telluride and copper indium gallium selenide (CIGS), are made of toxic or rare materials: cadmium is highly toxic and tellurium is about as abundant as gold.

So Hao decided to go back a step. “We’re trying to make the whole world ‘green’, right?” she says. “So, we should choose materials that are non-toxic and cheap, and that would ensure their deployment in the future – without constraint on raw materials.”

Her quest for a greener world began in 2011, after she returned from maternity leave. Hao and her PhD supervisor, Martin Green, knew what they were looking for: a mix of elements that would absorb and conduct energy from sunlight, and are commonly found in nature. “We worked our way through the periodic table for materials that met those criteria – CZTS was the one that popped out at you as worthy of investigation,” Green explains.

In 2012 CZTS – copper, zinc, tin and sulphide – was recorded for the first time in the solar cell efficiency tables, an internationally curated list of solar cell performance. Inclusion in the tables means a new cell has been independently tested for efficiency by a recognised test centre, and indicates the new cell has features that will be interesting for the photovoltaic community.

Hao began making her own version of the CZTS cell, looking for defects, ironing out the kinks and pushing efficiencies, bit by bit.

At the basic level, all solar cells absorb photons from sunlight and funnel them into an electric current. Hao discovered that tiny holes in her CZTS cells, formed as the components were baked during production, acted like a roadblock for that charge. By adding a microscopic grid layer through the cells, her team stopped these holes from forming, and raised their efficiency to 7.6% in a 1cm² cell. That was Hao’s first world record. By changing the buffer that helps the CZTS cell collect charge, the team could further tweak the current flow and voltage output. This buffer netted Hao another world record in September 2016 – a 9.5% efficiency for a 0.24cm² cell, beating a 9.1% record previously held by Toyota.

“We’re completely leading CZTS solar cell technology at the moment,” Hao says with a smile.

According to Hao, these records have already sparked interest from Chinese, US...
and Indian industry, including current partners China Guodian Corp – one of the five largest power producers in China – and Baosteel, the giant state-owned iron and steel company based in Shanghai. Hao is also in talks with thin-film manufacturers MiaSolé of the US, Sweden’s Midsummer and Solar Frontier in Japan. The companies are commercial producers of CIGS cells and their production lines use similar methods; Hao says they could easily adapt them for CZTS production.

Hao believes efficiencies of above 15% will start moving CZTS to the commercial market. She is already well on her way, aiming to bring her CZTS cells to 13% efficiency by 2018.

AFTER FOUR DECADES in photovoltaics research at UNSW, Martin Green has a healthy scepticism when it comes to marrying new breakthrough technologies with commercial markets. “The solar industry is just so huge that you need enormous resources to introduce a new product to the market – and there’s a huge risk associated with that,” he says.

With a firm grip on 90% of the commercial solar cell market, “the situation with silicon is a bit like that of the internal combustion engine,” Green explains. “That engine is not the best fossil fuel engine, but the huge industry supporting it means it has been very difficult to displace.”

But CZTS does not need to compete with silicon – the two can complement each other. Silicon absorbs light better than blue, while CZTS absorbs blue wavelengths better. A CZTS layer on top of a silicon cell can catch the wavelengths silicon does not use efficiently. Green says the big silicon manufacturers could trial the new CZTS technology by selling these ‘stacked cells’ as a premium product line.

“Companies that are well established would be interested in exploring that space – it just seems like a natural evolutionary path for photovoltaic technology,” he says.

JUST A FEW labs down the corridor of the Tyree Energy Technologies Building at UNSW’s Kensington campus, Anita Ho-Baillie is working with Green to put another ‘stackable’ thin-film solar cell through its paces.

In 2009, a material called perovskite arrived on the thin-film solar cell stage with an efficiency of 3.8%. Perovskites have since shot up in efficiency ratings faster than any other solar cell technology. After Ho-Baillie’s team found a new way to apply perovskite to a surface in an even layer, their solar cells broke three more world records in 2016. Her next step is to make perovskites more durable to match the current lifetime of silicon solar cells – an essential prerequisite for large-scale commercial deployment.

As the leader of the perovskites project in UNSW-based Australian Centre for Advanced Photovoltaics (ACAP), Ho-Baillie stands at the nexus of Australia’s greatest cluster of scientists pushing thin-film technologies forward.

This alliance consists of six research organisations around Australia: the national research agency, CSIRO; Melbourne’s Monash University and the University of Melbourne; the University of Queensland in Brisbane; the Australian National University in Canberra; and UNSW in Sydney. ACAP director Martin Green says, “We’ve been able to draw on the expertise of all these groups and come at problems from different angles, so it’s really put us in a good spot internationally”.

Ho-Baillie admits balancing collaboration with competition is tricky in a field where everyone is trying to claim the top spot. “It’s hard, but we find working together really helps,” she says.

Much like CZTS and other thin films, perovskite cells are flexible, making them a perfect candidate for energy-harvesting glazes on building materials, cars or windows. But Ho-Baillie has even greater ambitions: with their low weight-to-power ratio, perovskites would be perfect for supplying precious energy to spacecraft, where every kilo counts.

“Perovskites came from nowhere,” she says. “Now I think they will lead us to something that we never even thought would work.”

THIN FILMS ARE making their mark, but Green is also working to squeeze more energy from sunlight using silicon, smashing two more world records in 2016. Using specialised mirrors and prisms, Mark Keevers from Green’s team pushed silicon cells to collect concentrated sunlight with 40.6% efficiency, and un-concentrated sunlight at 34.5%.

Although these prototypes are perfect for soaking up photons on solar tower ‘concentrators’ with heavy-duty efficiency, their manufacturing costs are too high to make them viable in the consumer market. But on the rooftop, silicon is still king. And it’s thanks to plunging costs made possible by a UNSW-led boom in silicon solar cell production in China, which now provides more than half the world’s solar cells.

In 1995, Green and his long-term collaborator Stuart Wenham – along with (then) PhD student Shi Zhengrong – started solar cell company Pacific Solar in Australia. After six years racking up a wealth of management and manufacturing know-how, Zhengrong returned to his native China and founded the silicon solar manufacturing company Suntech Power in 2001, using technology developed at UNSW to dramatically reduce costs.
By 2005, Zhengrong became the world’s first ‘solar billionaire’, and a wave of Chinese companies hit the market, following Suntech’s recipe. The global solar industry was growing at an average 41% year-on-year. And within a decade, China’s market share of the global photovoltaic industry had grown from near zero to over 55%. Suntech itself delivered more than 13 million solar panels to 80 countries.

Where photovoltaic solar cells used to deliver one watt for US$76.67 in 1977, that’s down to just US49¢ today. That’s a 150-fold improvement in the 40 years Green has been in the field.

“Shi was the right person at the right place and the right time to move in both Chinese and Western cultures,” Green says. “It’s interesting to ponder what would have happened if UNSW hadn’t kick-started the Chinese industry.”

With plunging module prices, rising efficiencies and more durable cells, why is the world still relying on coal for the lion’s share of its electricity needs?

Perhaps it’s not the solar technology that we’re waiting for. A fundamental challenge remains: how to store the energy we can now capture from sunlight for later use.

“I think photovoltaics has already reached the tipping point – the efficiency and cost is already able to compete with fossil fuels,” says Wenham. “I think the next breakthrough needs to be in energy storage, to bring down that cost enough to make photovoltaics usable everywhere at any time.”

This doesn’t mean UNSW photovoltaics scientists are calling it a day. Instead, they continue to push silicon to its limits, while new technologies, such as Hao’s record-breaking CZTS tile, are racing to catch up to silicon’s powerhouse.

“Solar technology will continue to be higher-efficiency, lower-cost – and will keep getting better,” says Wenham. “The more we develop photovoltaic technology, the easier the transition will become.”

“We’ve reached a new era where coal is no longer the cheapest way of making electricity – it’s solar,” says Green. “And the exciting thing about that is – I regard solar as still in a very primitive stage of development, so there is plenty more cost reduction to come.”
Now, as Director of the Australian Centre for Advanced Photovoltaics (ACAP), he has his hand in photovoltaic research projects across UNSW and six ACAP member organisations across Australia. Green has seen his once prototype technology commercialised and on rooftops, has claimed many prestigious international awards and was elected into the Fellowship of the UK’s Royal Society in 2013.

After 40 years in the field, Green is now more a responsible parent than a revolutionary. Often called ‘father of photovoltaics’, he believes in steady progress: “We’ll see evolutionary advances in solar technology, rather than a quantum leap,” he says.

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In the 1960s, Martin Green was an engineering undergraduate student who became interested in microelectronics but didn’t like the idea of building TV electronics for a living. Instead he became hooked on an idea revolutionary at the time: harvesting the energy of sunlight for human use.

Green brought his skills in electronics to a PhD at McMaster University in Canada, where he made his first solar cell in 1971. In 1974 he seeded world leadership in photovoltaics at UNSW by founding what his long-time colleague calls “a small but brilliant team”.

His vision that solar cells could one day have a significant impact in a time when that was deemed near impossible inspired a productive culture. Just 10 years later, Green’s team dominated the field after breaking his first world record with a silicon solar cell efficiency of 18%.

STUART WENHAM BECAME enticed by solar cells as a hobby during high school in the 1970s. “They seemed to me like the closest thing to magic,” he recalls. “I was fascinated by the technology long before I could understand it.”

Attending the first UNSW course on solar cells, taught by Martin Green, inspired him further. Fresh out of an undergraduate degree in electrical engineering, Wenham moved into industry to set up Australia’s first solar cell production line, and it was this practical know-how which he brought back to UNSW to start a PhD with Martin Green.

It wasn’t until 1995, as he worked with Green to start up the company Pacific Solar to commercialise thin-film cells, that he began to realise solar cells were set to make a real impact. Since then he has fostered international ties by developing and commercialising UNSW photovoltaic technologies overseas, including as Chief Technology Officer of Chinese company Suntech for over 10 years.

As Director of the Centre of Excellence for Advanced Photovoltaics and Photonics at UNSW, he is still chasing breakthroughs. In 2014, he was awarded the £350,000 A.F. Harvey Prize by the UK’s Institution of Engineering and Technology for a revolutionary hydrogenation technology that can make any existing silicon solar cells more efficient.

In contrast to his early days, Wenham has no doubt solar will overtake fossil fuels to feed our electricity needs. Instead, he believes, it’s only a matter of time.

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UNSW will be home to the first Torch Innovation Precinct outside China, and the Australian and Chinese companies and research centres to be based at the new A$1 billion high-tech hub are themselves likely to generate billions in the coming decade.

A CEREMONY in Beijing’s Great Hall of the People in April 2016, Australian Prime Minister Malcolm Turnbull and China’s Premier Li Keqiang signed off on one of the most ambitious government-backed international research initiatives in recent history.

For the first time, the China Torch Program will establish a science park outside China, on the UNSW campus in Sydney, giving Australia access to one of the world’s largest and most successful entrepreneurship programs. The program accelerates innovation by strategically locating Chinese businesses, universities and research organisations in science and technology.

Since 1988, 156 Torch Program high-tech zones and science parks, hosting over 50,000 companies, have been built across China. The Torch R&D budget is more than A$40 billion – and Torch companies account for more than 11% of China’s GDP.

“Securing the Torch Project is an incredible recognition of how well UNSW is respected within China, based on our longstanding history,” says Mark Hoffman, Dean of Engineering at UNSW.

“It recognises that Australian technologies can play a significant role in industrial global development; and clearly China sees an opportunity that isn’t currently being exploited.”

Hoffman says the Torch concept has been very successful in producing the kinds of close relationships between industry and universities that lead to commercialisation.

“That’s a gap that Australia doesn’t exploit for a whole range of reasons, but a lot of Chinese industry does very
well out of the university system within China. I think they’re seeing that Australia – particularly UNSW – presents considerable opportunity in that regard,” says Hoffman.

Australia lacks companies large enough to make significant investments in technologies, and has less industrial diversity, he says.

The UNSW Torch project started operating in August 2016, and between them, 20 companies have already committed over A$60 million to Phase One of the project. By 2020, a five-hectare precinct will be underway, with a focus on cutting-edge innovation and R&D in energy and environment, advanced materials and biotechnology. Deloitte Access Economics estimates Torch companies could return some A$1.1 billion to the Australian economy.

Hoffman says a Torch Precinct in Australia will mean significant funds flowing into the country to fund local research. “This is work that simply wouldn’t be funded otherwise,” he says. He dismisses concerns about potential missed opportunities for manufacturing in Australia, as unrealistic. “If manufacturers in Australia wanted to do this, they would be doing it,” he says. “Under Torch, Australia will certainly get returns for that research.”

He believes the Torch Precinct directly supports a key UNSW mission – great research. “And in a global environment, research only becomes great when it benefits society and the world.”

Hoffman’s involvement in Torch goes back a long way. In 2014, as Pro Vice-Chancellor Research, he led the first UNSW roadshow to visit Torch Parks and various companies in China, and began building those relationships. Two more roadshows and many subsequent researcher visits cultivated that initial seed, he says, as did long-term alumni relationships. UNSW has hosted students from China since the early 1950s.

“The work in photovoltaics has a very close link to our alumni group. Many of the significant Chinese solar cell manufacturing companies are UNSW alumni,” he says. “We’ve got Australian companies keen to be involved with this network because it provides them with important linkages to Chinese industry.”

Torch Project Manager Yuan Wang has a crucial role in developing the new precinct. The senior chemical engineering academic has put most of her other work on hold to get the project up and running. “We’re all very excited about this. One of our first aims is to secure more than A$100 million in research funding from Chinese industry partners,” she says.

Phase One allows five years to secure that funding. During this period, a Torch Technology Business Incubator will be established on UNSW’s Randwick campus, housing up to 100 staff. UNSW has released about 1,000m² of prime laboratory and office space on its Kensington campus in Sydney for the Torch Program.

A scheme to encourage student start-up businesses will also launch in Phase One. Supported by the Chinese and Australian governments, it will include large-scale student start-up competitions open to young Chinese entrepreneurs currently studying in Australia, and to young Australians seeking to export their ideas to China.

Phase Two involves building infrastructure – labs, offices, accommodation and recreational facilities – on a UNSW-affiliated five-hectare science park near the existing campus. Tus-Holdings, a Beijing-based science-park development company backed by Tsinghua University, is contracted to do a feasibility study for Phase Two, assessing proposed sites, and investigating Australian policy and projected investment returns, to ensure the university gets the maximum financial return.

The Phase Two site is expected to provide an Australian research and development base for up to 10 major Chinese companies, together with a Technology Business Incubator supporting up to a 100 Chinese and Australian small enterprises.

But right now, Phase One is the focus. Four priority research areas – materials, energy, the environment and life sciences – have been identified. Wang is working on growing potential Category 3 funding (industry-funded contract research), improving connections with industry and increasing social engagement.

She already has around A$68 million in funds under ‘serious negotiation’, along with some A$26 million already committed. “It’s expanding more and more. We’re strong in manufacturing, ICT, social science, and there are more and more academics becoming involved, which is very promising,” says Wang.

“The main challenge is to find the most suitable partners in China, and align with the research strength at UNSW. Meanwhile, we’re just cracking on with our research, building partnerships, and getting some very initial-stage incubators on campus.”

Left: Zhongguancun Science Park in northwestern Beijing, home to nearly 30,000 high-tech enterprises.
“Every year, we blitz it,” says Buckland, head of the Security Engineering Lab and a professor of cyber security at UNSW’s School of Computer Science and Engineering. “So I think we’re doing something right.”

What he does right is organise courses that teach cybersecurity through a series of hands-on exercises, using cloak-and-dagger collaborative games that ignite his students’ enthusiasm. This approach

Australia’s hottest hackers come from one Sydney lab, led by an affable professor who is on a mission to fight cybercrime at the world’s biggest institutions and companies.
flips the standard teaching model, so that students are taught offence as a way to develop defence; and, in the process, come to understand the mindset of the hacker. “In addition, we partner with experts to bring in real-world scenarios to the classroom,” Buckland says. Sometimes, these are industry gurus in banking and telecommunications. Sometimes they are badass hackers.

“I can give the students an overview and tell them the theoretical aspects, but then we have cyber community leaders show them how to actually do it,” he says. “I think the role of teachers is to lift our students up above us.”

The program’s alumni have brought this collaborative ethos into the corporate world. “I’ve seen the emergence of a community of security professionals who work together, not just for the interests of their own company, but for security in general,” says Buckland.

There is a huge supply and demand problem for cybersecurity professionals. A recent report by US-based market research company Cybersecurity Ventures estimates cybercrime cost companies US$4 trillion in 2015, and is set to rise to US$8 trillion annually by 2021.

It’s a criminal epidemic that can only be fought by cybersecurity experts, a profession that is itself growing at a rate of 18% annually, according to the US Bureau of Labor Statistics. Cisco estimates there are more than a million unfulfilled security jobs worldwide. “In the early days, companies just repurposed rebels and old-style malcontent hackers, dressing them in suits and paying them lots of money,” says Buckland. “That was a really great solution. Until the pool ran dry.”

Now that cybersecurity experts need to be mass produced, the burden is falling to universities. “But no one worldwide really knows how to do it — there isn’t yet expertise on training up the rebels and breakers you want.”

To help quench demand, Buckland is developing a series of massive open online courses (MOOCs) for anyone to learn cybersecurity, as part of a A$1.6 million SEC.EDU partnership with the Commonwealth Bank of Australia to expand UNSW’s cybersecurity teaching resources and curriculum.

Already, almost 20,000 budding cyber defenders have signed up to the introductory course, 60% of them from Australia, ranging from information technology professionals wanting to brush up on the latest technical knowhow, to schoolchildren — even miners and taxi drivers who want to reskill.

Perhaps most crucial are the many teachers and lecturers taking the course, exponentially increasing Buckland’s reach. “For university academics who have been brought up in a traditional non-hacker way, cyber is a little bit scary to teach,” he says. “Academics can borrow our lecture notes and course materials, or just be influenced to — I hope — become believers in the particular way we teach cyber.”

Buckland’s MOOC is hosted on Open Learning, Australia’s first MOOC provider and a company he co-founded in 2012 with former student and now chief executive Adam Brimo. Designed to deliver more engaging courses online, the platform features lecture videos and exercises, along with wikis and social media-style technologies to allow people to interact and collaborate.

And Buckland is not just focusing on young adults and professionals. Aiming to instil a cybersecurity mentality at an early age, he goes into primary schools to teach kids the basic mindset of a hacker and how to protect against cybercrime. “I’m trying to get the kids to scam each other in a controlled way, because I think then they get to understand how scams work and how to be defensive against them.”

**Cyber defender: Richard Buckland at work with students.**
CORE CODE

WE TRUST COMPUTER systems every day – but trusted systems are rarely entirely trustworthy. Laptops can crash, servers can freeze, and personal details can be stolen. Even pacemakers can be hacked.

“The complexity of the systems we’re building has grown much faster than our ability to deal with it,” says Gernot Heiser, a professor of operating systems at UNSW and chief research scientist at Australia’s digital research network, Data61, a division of the national science agency CSIRO. “The result is an appalling lack of dependability.”

“As critical tasks like controlling medical devices, mobile phones, industrial plants and airplanes become ever more technology-dependent, trust should not be taken for granted,” he adds.

Is it even possible to write truly trustworthy code? Heiser thinks so – which is why he has spent the past decade developing secure microkernels, the core on which dependable operating systems can be built. By itself, a microkernel does not provide useful services, but contains the core mechanisms on which to build them.

Working with UNSW colleagues Gerwin Klein and Kevin Elphinstone, Heiser sparked excitement among experts when the team proved that all 7,500 lines of C code in his seL4 microkernel were mathematically correct. May not sound like much, but this is incredibly difficult to achieve.

“It is hard to comment on this achievement without resorting to clichés,” quipped Lawrence Paulson, a noted leader in theorem proving and a professor of computational logic at the University of Cambridge. June Andronick, a principal research scientist at Data 61, who specialises in the verifiability of software systems, adds: “What Heiser and his team have done, and keep doing, is to strengthen the guarantees that can be provided about software by orders of magnitude, while maintaining very good performance for real-world use.”

A big test of Heiser’s seL4 microkernel came in 2015, when the US Defense Advanced Research Projects Agency gave hackers unfettered access to the on-board computer of an autonomous Boeing AH-6 helicopter gunship. Their task was to hijack the microkernel and take control. While hackers easily commandeered the helicopter when it hosted other software, they could not crack the on-board computer when it ran on seL4.

A predecessor of the secure seL4 software – known as OKL4 – may already be in your pocket. Heiser set up Open Kernel Labs in 2006 to commercialise his OKL4 microkernel. The company was later bought by General Dynamics, after which “our technology ended up in the pockets of billions of consumers,” says Heiser. OKL4 is now on the security processor of all Apple iOS devices.

But there are still important weaknesses. “Observing exact timings of actions can leak secrets, via so-called ‘timing side channels’, giving attackers the ability to eavesdrop on communication or even masquerade their malicious code as legit services,” says Heiser. His team is now working to prevent such failures by blocking any given process from unduly influencing the execution speed of another process – and eventually proving that this works.

The second weakness is price. The development cost of the seL4 microkernel was about three times that of comparable unverified, vulnerable software. But Heiser thinks he can make the software affordable for everyone. “If we manage to eliminate this factor-three cost gap to standard software, we’re totally changing the world of software systems.” — Ben Skuse
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