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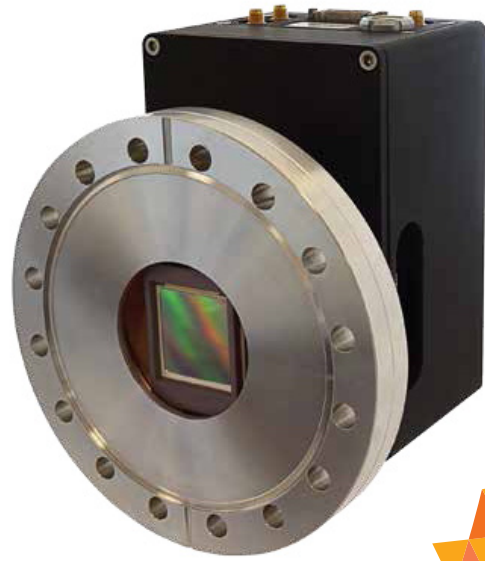
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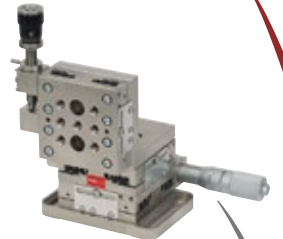Photonics Technology Solutions

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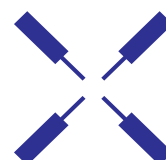→ Low trigger latency with ultra-low jitter

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CONTENTS

The Vulcan high peak power laser, at the Science and Technology Facilities Council's Central Laser Facility (UK), striking the surface of 0.1 mm thick tantalum slab. The pulse delivers 250 J in 1 pscosecond onto a spot of 5 micron diameter, generating a high energy density plasma that emits relativistic energy particles and photons. The visible cones of beams originate from frequency doubled infrared laser light, which is generated during the extreme laser-matter interaction and deflected by the ballistic metallic blow-off from the surface.

GUIDELINES TO CONTRIBUTE
Articles or other items for submission to Australian Physics should be sent by email to the Editors. Only MS Word files will be accepted; a template with further guidelines is available online at the AIP websites (www.aip.org.au).The Editors reserve the right to edit articles based on space requirements and editorial content.

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EDITORIAL

STIMULATED & AMPLIFIED

Welcome to the last issue of Australian Physics for the year. And while we collectively brace ourselves for the silly season, you might ask "Where on the cover are the stars, snow flakes and other Christmas ornaments?" Under the Australian sun, something from a laser just seemed more appropriate.
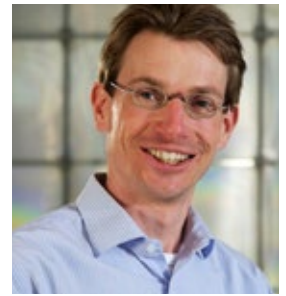
That image, we felt, is pretty striking, telling a tale about matter squeezed into extreme conditions in an instant or two. In our opinion, such dramatic 'blastology' experiments can usefully reflect nature at its most messy and extreme and, at the tail end, lead to application. Not everyone will agree – we welcome dissent at aip_editor@ aip.org.au .

Lasers are also a good representative of precision, a silver strand spun into the thread running through this issue of Australian Physics. Detecting gravitational waves, solidifying the Système Internationale, building flux capacitors (you can imagine the cover we chose not to run, with a small sigh of regret), are all linked by that strand of precision. But that thread would be incomplete if there were not that golden strand of the human element of science. Precision and emotion are combined into one as the spinning wheel turns. Together they lend strength to the thread of physics weaving into the fabric of progress, innovation and society. Society in turn looks to us to tell stories about our research and discoveries.

Wrapping emotion and humanity around issues can be an effective way to tell stories. Teaching successfully draws on one's own passion to inspire and take students on a believable journey. Prizes and other formal acknowledgements are also instrumental in getting our stories across. In this issue, we have two reflections from prize winners that do just this.

We would also like to issue a call for physics pictures: imagery that tells a story that connects your work, your research, your discoveries with the community, with yourself, with the people near you; imagery that conveys meaning, truth and precision; imagery that makes you reflect or that you wish would make others reflect on important issues. Send them in with a short description of the story attached.

And last but not least, congratulations to AIP President Andrew Peele for being appointed Fellow of the Australian Academy of Technology and Engineering, ATSE! We are keen to hear more as time progresses.

To all readers, have a very happy and relaxing Holiday Season and best wishes for 2019!

Peter Kappen and David Hoxley

PRESIDENT'S COLUMN

AWARDS IN A NOBEL CAUSE

October is a good time of year for awards with the Nobel Prize and the Prime Minister's Prizes for science both announced. I was privileged this year to go to the ceremony for one of these awards; I will let you guess which one, and watching events unfold reminded me of the value of awards and recognition.

Just what is the value of a Nobel Prize in physics? An obvious answer is the nine million Swedish kronor (about $AU 1.4 million) that was given out this year. Some less obvious answers include the value of the metal in the medal itself (about $AU 10,000), what a medal would fetch at auction (Chadwick's 1935 medal for the discovery of the neutron sold in 2014 for $US 329,000), and even the speaker's fees that can be commanded by a Nobel laureate (upwards of $AU 10,000 a talk). Harder to quantify is the value the award brings to the discipline thanks to the free publicity and recognition of what are some of the most important discoveries in physics.

Offsetting these estimates of value are deficits related to issues that are raised by critics of the Nobel prize. For instance, what are the ethics of receiving a prize bequeathed from the will of a person who received (in a premature obituary) the soubriquet of the Merchant of Death? Does it damage the discipline to focus on individuals (or at most three people) when many physics discoveries are the work of large teams. And what is the detriment to the discipline when 3 out of 209 physics laureates are women?

How we balance value against deficit is a judgement call that depends on the importance we place on certain things and the way we perceive progress being made to mitigate against the negatives. In the case of Alfred Nobel, should we deny his attempt to leave a positive legacy after having read that obituary? There might be a case for seeking to have teams recognised, but if the committee refuses to do so are we really suggesting we should boycott or stop an award that garners so much recognition? On the other hand, the bias in the award to men is such that even allowing for participation rates of women in physics the chances of all laureates between 1990 and 2013 being male was found in a published study to be less than 2%.

The news that Donna Strickland is the first female laureate since Marie Goeppert Mayer 55 years ago is inspiring and a just recognition "for groundbreaking inventions in the field of laser physics" and, in Donna Strickland's case, shared with Gérard Mourou "for their method of generating high-intensity, ultra-short optical pulses." This work was both elegant and profound in that it realised a simple idea that a pulse could be stretched in the time domain, allowing amplification, and then compressed again for high power thus paving the way for the intense and ultra-short pulses of light that can now be used to probe molecular dynamics and chemical reactions.

Great work, great recognition, but how should we respond to an institution that has seen fit to give one award in physics to a women in over 50 years? There is some good news in that it has been reported that the Swedish Academy is asking for biases be considered by nominators. Ultimately, the value of an award like the Nobel Prize will be determined by how reflective it is of the values of the community.

This discussion is highly relevant for the Australian Institute of Physics. As president, I am acutely conscious of the fact that we have several awards that have either never been won by women or have very low representation. We have made changes, particularly in the make-up of the judging panels, but, like the Nobel Prize, we should be judged on the results. We should not expect instant equal representation, but we should see a positive trend.

The Prime Minister's Prizes for Science is a modern award made at the national level. Of the past 19 winners of the Malcolm McIntosh Prize for Physical scientist of the year, 5 have been women. Somewhat better than the Nobel. Whether it is good enough is a question that the community should be vocal about.

One aspect of balance that, I think, is managed well by the award is that of party politics. For something called the Prime Minister's Prize, the temptation might be to turn the event into a showcase for the government of the day. However, good representation, for the major parties at least, is managed during the ceremony and our senior politicians (often the Prime Minister and the leader of the opposition both speak and this year we also heard from the Minister for Science) all speak well as to the importance of science for our society.

Finally, and while on the topic of balance and representation, it is pleasing to see that physics has done pretty well in winning 11 of 19 Malcolm McIntosh awards for Physical scientist of the year and that 4 of the 5 women to win the award are physicists!

Andrew Peele

NEWS & PERSPECTIVES

Editors' note: This years' Nobel Prize in Physics is important news. Before we get to that, we would like to first celebrate our local recipients of honours. So, congratulations to Dr Richard Manchester, FAA, and Prof Ross McPhedran, FAIP, for receiving prestigious awards in astronomy and composite science.

Pulsar pioneer honoured

Australian and New Zealand astronomer, and former Editor of *Australian Physics* Dr Richard (Dick) Manchester FAA has been awarded one of Australia's highest honours for work in the physical sciences, the Australian Academy of Science's Matthew Flinders Medal and Lecture.

Dick Manchester is an Honorary Fellow with CSIRO Astronomy and Space Science (CASS) and is a world-leading authority on pulsars. In a career spanning over fifty years, Dick has led teams that have discovered more than 1700 pulsars, about 60% of all pulsars now known.

Among the pulsars Dick and colleagues discovered is the only known double pulsar, listed by the journal Science as one of the top ten scientific breakthroughs in 2004. The discoveries have been used to test Einstein's General Theory of Relativity, to search for gravitational waves from super-massive black holes in the early Universe, to probe magnetic fields in our Galaxy and to explore supernova explosions.

Professor Ron Ekers, a former director of CASS, described Dick as a 'tour de force' of Australian astronomy: "His contributions to both international radio astronomy and Australian science have been substantial. In 1985, he published a seminal research paper on the Galactic pulsar population and its evolution, which for the first time gave a clear indication of how many pulsars exist in the Galaxy, how long they lived and how they evolved."

In 1977, Manchester co-authored the definitive book 'Pulsars' with Joseph Taylor (U. Massachusetts), who was awarded the 1993 Nobel Prize for his pulsar research. In 2008, Dick was invited to Cambridge to give the inaugural Hewish lecture, named in honour of Antony Hewish, the co-discoverer of pulsars.

Manchester said he was greatly honoured to receive the award. "It has been a huge privilege to be able to follow my instincts in astrophysical research in a relatively unhindered way for the past fifty years and I thank all those that have made this possible."

He added: "Pulsars are fascinating astrophysical objects that tell us a lot about the way the Universe works. My research has been a wonderful vehicle for exploring topics as diverse as the theories of gravitation and the structure of the interstellar medium in our galaxy."

Manchester is the fourth radio astronomer to receive the award, joining Joe Pawsey (inaugural winner 1957), Paul Wild (1974) and Ron Ekers (2005). Dick will be presented with the medal in May at the Academy's Shine Dome in Canberra, where he will deliver the Matthew Flinders Lecture.

(AAS press release and Peter Robertson)

Rolf Landauer Medal Awarded to AIP Fellow Ross McPhedran

At the 11th Conference on the Electrical, Transport and Optical Properties of Inhomogeneous Media (ETOPIM 11) held in Krakow, Poland July 16-20 2018, Professor Ross McPhedran was awarded the Rolf Landauer Medal for research excellence in the field of composite science. He shared the award with the eminent solid state theorist, Professor Ping Sheng, of the Hong Kong University of Science and Technology.

The citation reads: "Ross McPhedran has made important basic contributions to the theory of electrical and optical properties of inhomogeneous media, starting before the first ETOPIM Conference in 1977 and continuing to this present day. In 2006 he founded the International ETOPIM Society and chaired it until 2012. Both Landauer Medallists participated actively in most of the ETOPIM Conferences. Both have organised one such and have contributed significantly to the success of many of the others. Both have educated a significant number of researchers in the fields of ETOPIM and in this way have helped to populate those fields with outstanding scientists."

Ross McPhedran was further honoured with the dedication of the 11th ETOPIM Conference to him on his seventieth birthday.

Professor Ross McPhedran (right) being awarded the Medal by Professor Graeme Milton of the University of Utah, an eminent graduate of the School of Physics at the University of Sydney.

2018 Nobel Prize in Physics also a celebration of the power of diversity

The first half of this year's Nobel Prize was awarded to Donna Strickland (Canada), and Gerrard Mourou, France, for their work on creating lasers with ultrashort pulses. In the 1980s, they were curious about how to amplify laser pulses while avoiding nonlinear processes that lead to instabilities. Their elegant trick is to first expand the pulses in time, then amplify and compress them back in time. This has led to many unforeseen applications in medicine, materials processing and eventually to pulse of just one optical wave. The two worked together as a team and the Nobel Foundation recognised both partners in this collaboration. Professor Strickland is only the third woman to receive this honour in Physics, after Marie Skłodowska Curie (1903) and Maria Goeppert-Mayer (1963).

The second half of the prize goes to Arthur Ashkin (USA), who recognised in the 1970s that particles and atoms experience forces when they enter a laser beam. The combination of radiation pressure and laser gradients inside a beam can thus trap and move small particles. This insight led to the development of optical tweezers, now a widespread tool for investigating biological systems, from mechanical manipulation of sections of DNA to moving objects inside living cells and organisms. All three scientists used curiosity-driven research to vastly increase the usefulness of lasers at the core of widely used instruments

Falling Walls Lab – Removing barriers

Falling Walls Lab Australia is part of a Berlin-based international ideas competition. Participants present their research work, business model, or initiative in a 3-minute pitch to a high-calibre jury of experts from academia and business. This November, at the anniversary of the fall of the Berlin Wall, our two winners will represent Australia in Berlin in the ideas contest of 100 bright young minds. Samantha Wade from the University of Wollongong shows new chemo therapy implants to treat pancreatic cancer, and Hayley Teasdale from University of Canberra demonstrates new technology to help improve balance and prevent people from falling. Now in its third year, the Australian Lab is organised by the Australian Academy of Science and the German Embassy in Canberra. Bring your new ideas to next year's Falling Walls event.

Left to right: Alan Finkel AO, Australia's chief scientist; HE Dr. Anna Prinz, Ambassador of the Federal Republic of Germany; Samantha Wade, Winner FWL Australia 2018, Anna-Maria Arabia CEO of the Australian Academy of Science.

(photos: Australian Academy of Science)

AIP Women in Physics Lecture Tour 2018

Ceri Brenner
Senior Application Development Scientist
Central Laser Facility, Rutherford Appleton Laboratory, Harwell Campus, UK – ceri.brenner@stfc.ac.uk

In August I travelled across Australia as the AIP's 2018 Women in Physics Lecturer – a fantastic opportunity to engage the next generation of scientists and the public with our profession, and to learn about and meet the Australian physics community. I came with a mission – to enthuse with the extreme state physics generated with the world's most powerful lasers, and to inspire with stories of collaboration, creativity, and innovation with laser-plasmas to showcase the side of physics that I love – orientated discovery research.

Imagine terawatt lasers that can heat a pea-sized blob to keV bulk temperatures within a few nanoseconds while imploding it to several times the density of lead. Or petawatt lasers that generate fully ionised plasmas within the first few femtoseconds of the pulse and then subsequently accelerate mega-amp currents of relativistic electrons into solid density foils that establish teravolt/metre acceleration fields to expel 1012 ions in a picosecond bunch duration. Everything about the field of high power laser-plasmas is extraordinary. It is extreme physics and it's being put to work for extreme applications. Whether it's laser-fusion for providing clean, sustainable energy or laser-accelerators for cancer treatment and industrial non-destructive testing, laser-plasma physics is translational research - a bridge between discovery and applied research. Researching the fundamental physics underpinning extreme laser-matter interactions is contributing towards solutions for global grand challenges – this is what Sir Paul Nurse describes as orientated discovery research. Traditionally, the laser-plasma physics community has been made up of people asking fundamental questions about the universe – how it works and its origins – as well as people trying to understand extreme interactions in order to apply them for a societal benefit. Now, there are also those who are preparing to use the newest generation of ultra-relativistically intense lasers to experimentally explore quantum electrodynamics! Laser-plasma physics engages people who love the 'wow' moments of science as well as those who ask 'why should I care?' – there's something for everyone and that is why it's a great subject to capture the attention of, and inspire, the next generation of physicists and the general public. However, the field is very small and often unheard of, so for me this tour was an opportunity for both public and academic outreach.

In just 3 ½ weeks I travelled across 6 states and spoke to young, old, scientists, non-scientists - I gave talks at schools, universities, and even at an art gallery! And, much to my amazement, I made it onto ABC's The World for a live interview about the physics and applications with high power lasers and being a woman in physics – a first for me that I won't forget in a hurry. You can follow the twitter coverage of the tour, with photos and videos, by searching for #AusWIPtour. The foundation of all my talks was the physics and the applications of the physics, but I also chose to intersperse with some of my own life experiences – the good and the bad – and to talk about the process of science and discovery and the teamwork behind it. This was an opportunity not just to promote my field but to educate and encourage my audiences, to rethink what physics is as a profession, to consider the skills that make a good physicist, to broaden

their viewpoint on the people behind the physics, to create an uplifting and welcoming experience of physics much like going to the theatre. I will be delighted when we reach the day when 'physics is hard, I probably won't understand it' is rarely heard. Yes, the detail, the mathematics and the tools of physics, the depth and the complexity can sometimes be hard, but do you really need to share all the difficult bits to communicate the concepts or the value of the physics? Of course you don't, and in my talks I aim to leave the audience with a few key messages and new pieces of information in the hope to replace their fear factor of physics with the 'warm fuzzy' feelings of intrigue and fascination that inspired us all to enter into this profession ourselves.

See it to be it

I was highly aware that I was there not just as an ambassador for physics but as an ambassador for women in physics. This lecture series is a platform to showcase women as physicists. Increasing our visibility is effective for changing people's perceptions of what and who physicists are. So often I had feedback from young women saying that meeting me and hearing about my job made them realise that this subject could be for them too and that they were inspired to look into physics and engineering to reach their life goals – to be part of something big, to travel the world, to make a difference. The 'see it to be it' style campaign is being used in all sorts of industries where gender parity, especially in leadership positions, does not exist. For sports, performing arts and media, and now science and engineering. By boosting the visibility of women in these jobs we provide role models and sources of inspiration that counteract the discouraging and wrong assumption that women are less suited to these roles. Still today it is a common assumption that physics is a male subject; what a damaging disservice to our profession. Increasing the number of people engaged with physics and those who wish to enter our profession is important – more people, more ideas, more discovery. We need to be able to tap into the entire talent pool available and if we discourage half of that talent pool from considering physics as a career then we are all missing out. As I write this, the 2018 Nobel Physics Prize has just been announced. I was absolutely delighted to see that is has gone to inventions with lasers and especially thrilled to watch chirped-pulse amplification – the discovery that enabled high power lasers – have it's time in the Nobel limelight. It was a special moment too in the equal recognition of Gerard Mourou and Donna Strickland – the first time in 55 years that a woman has been recognised for her vital contributions to the progression of physics. The world's media jumped on this and rightly so – here is the 3rd woman in history to be made a Physics Nobel Laureate. And also, I should add, someone who made that discovery while a PhD student – providing a clear example that you can make discoveries that will change the world regardless of gender or career stage. Increasing diversity in physics doesn't have a single solution though and that's due to it being a highly convoluted effect of social conditioning, cultural influences, image issues, and unconscious bias. We need to update the image of physics and update the way we engage with the public and next generation. Will making women more visible break down stereotypes and inspire a more diverse workforce in physics? It's a great place to start.

Asking the big questions

Engaging with an audience is as important as good communication to an audience. Being approachable and open to debate and discussion can bring down barriers. I find the questions at the end of a talk to be really valuable – they reveal which parts of the talk hit home with people and they also offer a chance to have an honest discussion about the topics raised. It's especially fun when I don't know the answer and I am very happy to admit when I don't – it's not a weakness - it's important for an audience to know that we don't know the answers to everything – if we did then we would be out of a job! I had a few questions (and the best ones were from year 10 and 11 students) that were 'what would happen if…?' or 'has someone tried….?' and my way to answer was to say 'I haven't heard of anyone doing that but that would make a great PhD project – want to be the one who finds out?' To me, being a good physicist is being able to ask a question that no-one has ever asked before – the more imaginative the better – and knowing the steps you need to take in order to answer that question with critical thinking. Asking

a question out loud in front of everyone else is not for everyone though. The gender disparity on this was stark and consistent in every school talk and public talk I gave – it's the same in the UK as well. One-on-one questions and interaction with people after the talk is so valuable because of this – I had the most impactful conversations with small groups of young women that revealed their deep understanding, interest and admiration for what they'd just heard, smashing all conceptions that a reason there are fewer women in physics is because they're just not interested. For anyone who does outreach and public speaking I really encourage you to be mindful of this and to make an effort to be available for those who need a quieter interaction to approach you afterwards for those valuable conversations. The 'Girls In Physics Breakfasts' were a really good way of providing that with small tables of students paired up with physics undergrads and researchers to facilitate conversations away from the very exposing arena of an open Q&A session.

Australia's Role?

Australia doesn't have a high power laser nor does it have laser-plasma physics community, so I really enjoyed introducing people to this for the first time. My talk 'Dream Beams: laser-driven accelerator technology for medical, nuclear, and aerospace applications' was designed with that in mind, so it only contained the key basic ingredients of plasma physics but a lot of examples of the industry engagement that is inspiring the projects I'm working on now. We're entering a new paradigm in high power lasers at the moment with the emergence of diode-pumped high energy systems and technology that is breaching the 1 petawatt level. The DiPOLE100 laser, built by my colleagues at the Central Laser Facility and delivered to HilASE facility in Czech Republic in 2016, was the first high average and high peak power laser in the world – 100 J in each pulse with nanoseconds duration and 10 Hz repetition rate. The first 10 petawatt laser has been built by Thales and is currently being commissioned in Romania, while the first 10 Hz petawatt laser, made by Lawrence Livermore National Laboratory, was delivered this year to the Extreme Light Infrastructure in Czech Republic, and new petawatt facilities are opening up in China and India for the first time. All these facilities are dominated by research programs that are focused on developing plasma accelerators and laser-driven sources of photons, electrons, ions, harmonics, terahertz emission, neutrons, positrons, and even muons, or focused on the science and industry applications of these bright, ultra-short pulsed beams. Does Australia want to join the club? If it does then I spotted a couple of possible locations.

Feels like home

I had a great time visiting the ANSTO sites at Lucas Heights and Clayton – I work at the Rutherford Appleton Laboratory in the UK which houses, in addition to the Central Laser Facility, the Diamond Synchrotron Source and ISIS Neutron Source, so these places felt most like home for me. I especially enjoyed the Australian native zoo of neutron beamlines, touring the nuclear reactor (my first time at a reactor!) and hearing how it is being used for nuclear isotope provision, and visiting the synchrotron imaging beamline that is being developed for mammography – can you tell I enjoy medical physics? Talking of which, I am immensely pleased to learn that proton therapy is coming to Australia. Proton therapy was my initial motivation for studying laser-accelerators as an alternative concept for delivering proton and ion beams for this sought-after cancer treatment – I was astonished it took me so long to come across that application of physics so it's now a prominent part of my schools and public outreach talks as it has such a powerful social impact.

Physics, Industry, and Innovation

As an application development scientist a large part of my role is industry and academic engagement. I'm currently focused on R&D of laser-driven X-rays beams as they have the unique combination of bright, highly energetic photon emission (> 1 MeV) from a source point < 50 μm which enables high resolution tomography of large and dense objects. This imaging capability is in high demand for industrial inspection and so I've teamed up with nuclear materials scientists, advanced manufacturing engineers, and various R&D engineers from aerospace and nuclear companies to start the conversation of how they want this technology to perform, the needs that it is addressing, and the scenarios that it will greatly impact. This is turn has inspired the direction of my research and the optimisation of certain parameters in order to meet these performance values.

3.5 weeks, 6 states

Devonport, to Launceston, to Hobart, to ANSTO Lucas Heights, to Perth, to Wollongong, to Sydney, to Adelaide, to Canberra, to Toowomba, to Ipswich, to Brisbane, to Melbourne, to Ballarat, to Bendigo, and finally to the Australian Synchrotron. It was a whirlwind ride - 10 internal flights, 10 different hotel rooms, 35 talks in total of which 14 were school talks (mostly years 10 - 12), 8 public talks, 11 academic seminar lectures, and 2 Girls In Physics Breakfast talks. It was a feat of endurance for sure, but an absolute delight to see so much of this beautiful country and to meet so many people. Driving across Tasmania, seeing the starry nightsky like I've never seen it before in Toowomba, spotting a mob of Kangaroos in Canberra, whale watching in Sydney on my birthday, overlooking the coastline on the way to Wollongong, looking out at the bright city landscapes of Brisbane and Melbourne at night, discovering that Vegemite is better than Marmite (!) - I have so many memories to treasure. Everyone I met along the way made this trip so memorable and special - that was the real highlight for me. I also had the chance to meet a bunch of people who are now my role models - group leaders, directors, CEOs and innovators. The networks I have formed from this trip are an extremely valuable takeaway from the tour – the Women in STEM group at University of South Australia, the Women in Physics groups at Flinders University and in Melbourne, and the local hosts from each branch. A special shout out goes to Joanna Turner, Gail Iles, Jodie Bradby, Dan O'Keefe whom I got to know well during our short but intense time together and hope to stay in touch with.

I set out to spread the word that physicists don't just answer the big questions about how the Universe works, but that we also use our knowledge to design solutions for some of the biggest challenges that we face. Oriented discovery research undertaken with a vision or goal is halfway between blue-sky science and applied science and is a great place to be in physics. I began and ended each of my talks with a message that I borrowed from Einstein -"imagination is more important than knowledge" - I hope it raises discussions about the role of creativity and imagination in science as I really believe these are our core skills. And in highlighting these as being as important as, for example, maths skills then we will attract and retain a more diverse, proactive, progressive and effective physics community. So cheers to that!

About the author

Dr Ceri Brenner is a senior application development scientist at the Science and Technology Facilities Council's Central Laser Facility with a unique role spanning research, innovation and technology development. She specialises in the physics governing extreme photon intensity (> 1018 W/cm2) interactions with matter and the subsequent particle acceleration and suprathermal electron transport through matter that gives rise to bright picosecond flashes of electron, X-ray, ion and neutron beams. She is collaborating with aerospace, nuclear and advanced manufacturing companies and organisations, and university groups, to apply these beams for non-destructive imaging and inspection applications. Ceri received her PhD in 2012 from University of Strathclyde on the subject of high brightness laser-driven proton beams for fusion ignitor schemes, radioisotope production and neutron generation.

In 2017, she was awarded the UK Institute of Physics Clifford-Paterson Medal and Prize for her significant contributions to the application of physics in an industrial context.

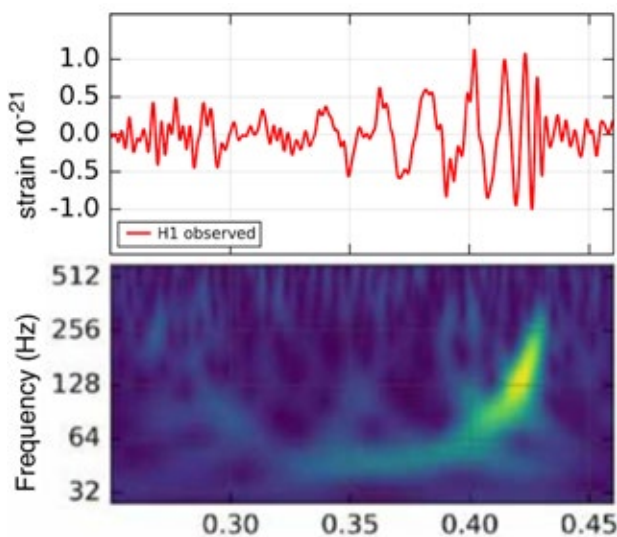# From gravitational wave detection to gravitational wave astronomy

David E. McClelland
ARC Centre of Excellence for Gravitational-wave Discovery,
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We continue our series of AIP prize winners, here by the 2017 Walter Boas Medalist. This medal celebrates research excellence in physics in Australia.
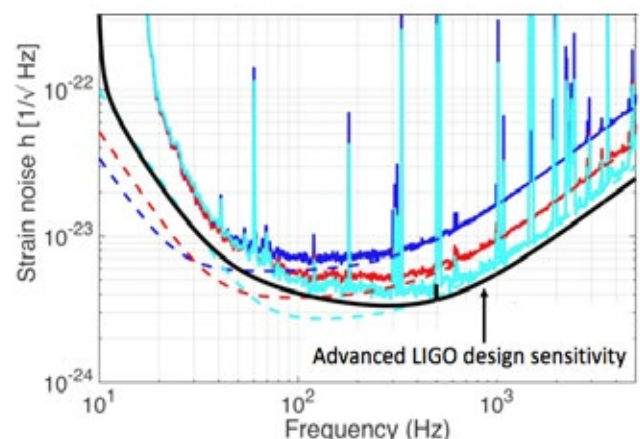
I was humbled to receive the 2017 Boas Medal, which I see as not only an individual accolade, but also as recognition of the important role played by a team of Australian researchers in the direct detection of gravitational waves. First detection occurred on September 14, 2015, during LIGO's first observing run, labelled O1 (see Figure 1). I summarised the Australian contributions in a previous article in Australian Physics [1]. Our direct contributions, built on over a decade of R&D, included: small optics suspensions; armlength length stabilisation and lock acquisition systems; Hartman cameras for monitoring beam distortions and errors; understanding and control of parametric instabilities; component installation and detector commissioning; signal test injections; data quality analyses; and search algorithms.

The first observation was of the merger of two high stellar mass (on the order of 30 solar mass) black holes referred to as a binary black hole (BBH) event [2]. We label events using 'GW' followed by the date (American style). So, this first event is referred to as GW150914. During the O1 run, which ran until January 12, 2016, the LIGO detectors typically achieved sensitivities that would enable them to observe such BBH events out to about 600 Mpc (1 Mpc is about 3.3 million light years). Two more events were observed (LV151012 and GW 151226 [3]) during O1.

A period of commissioning followed for about one year, pushing the range of the LIGO detectors for binary black hole systems like GW150914 out to more than 900 Mpc. The second observing run commenced on November 30, 2016, and ran until the August 25, 2017, with the Virgo detector (all be it a smaller sensitivity) joining in the second week of August. This run was also extremely exciting. To date we have three confirmed BBH signals

Figure 1: The gravitational-wave event GW150914 as observed by the LIGO Hanford detector 6.9 ms after the event was seen in the LIGO Livingston detector enabling LIGO to determine it position to within the annulus shown in Figure 3. The signal was in band (above 30 Hz) for about 200 ms. For presentation purposes, the time series is filtered with a 35–350 Hz band-pass filter. Top row, H1 strain. Bottom row: A time-frequency representation of the strain data, showing the signal frequency increasing over time (the 'chirp').

Figure 2: aLIGO Sensitivity evolution. O2 (dark blue curve) was the Livingston sensitivity at the end of the second observing run. The red curve shows the impact of increasing the laser power to 50W. Cyan curve includes 3dB of squeezing enhancement. Solid black curve is the goal aLIGO sensitivity.
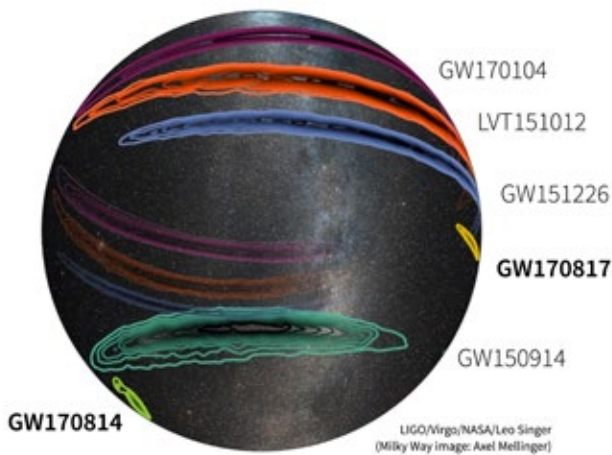
Figure 3: Skymap of reported gravitational wave events. The smaller the area of the coloured shapers, the better the localisation of the event on the sky. The light green at the bottom left is the triple coincidence BBH event. The yellow ellipse at the equator on the right is the BNS event.

[4-6] with one of them, GW170814 [6], seen by three detectors for the first time; analysis of the data is still ongoing. The skymap in Figure 3 dramatically shows the impact of having a three-detector network. With only the 2 LIGO detectors (see for example GW150914, GW151226, GW170104), it is impossible to achieve any reasonable location for the source. All we know is the source is located within some large arc on the sky. However, GW170814 shown in the bottom left, was detected in all 3 detectors, enable sky location to within a small patch.
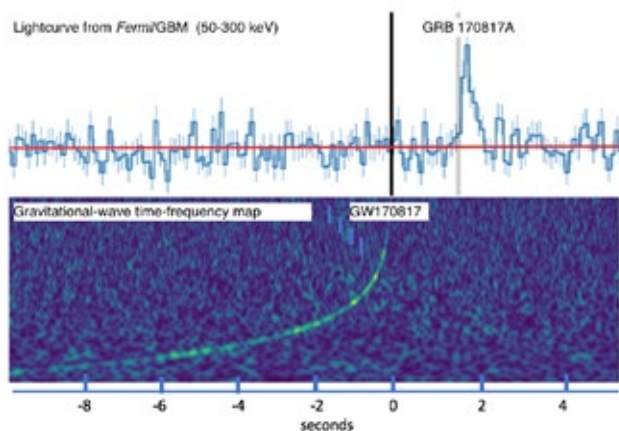
And then on August 17, 2017, the GW network observed a dramatically different event. BBH signals typically last a few tens of milli-seconds. The time frequency map for GW170817 [7] is shown in Figure 4, bottom

Figure 4: Bottom panel: time frequency representation of gravitational wave emission from the binary neutron star merger GW170817. In total the signal was in band (above 30 Hz) for 60 seconds. Top panel: Light curve observed by the Fermi satellite showing GRB 1709917A.

panel. This event was observed for around 60 seconds! Three detector data localised the source to within the yellow patch shown in Figure 3 (mid right hand side). Alerts were sent out to the astronomical community. Subsequent analysis showed that 1.7 seconds after the merger, gamma ray burst GRB17017A was observed in the same patch of sky [8] (Figure 4 top panel). More than seventy electromagnetic observatories trained their telescopes on this part of the sky and the event was observed in the radio and optical bands. These combined GW and EM observations confirmed the first observation of GWs from a binary neutron star merger; that short gamma ray bursts are generated by such mergers; that in the resulting kilonova the energy emitted produced the environment for creating most of the heavy elements in the universe; and enabled a new way to measure the Hubble Constant. This new era of multi-messenger astronomy had begun in a most spectacular way. Hundreds of papers have now been published based on this event.

The first three years of gravitational wave astronomy have been truly exciting. New discoveries and new information about known sources is an amazing start for a new window into the universe, with the truly unknown waiting to be revealed. Over the next few years, LIGO and Virgo will be brought to their design sensitivities (see Figure 2, black trace for Advanced LIGO, aLIGO) during alternating periods of commissioning and observation. Observation run 3 (O3) is slated to begin in the first quarter of 2019 with a BBH range of about 1200Mpc and BNS range of around 120Mpc. It is likely that few BBH events and about 1 BNS event will be observed each month! A 4th detector, the Japanese KAGRA [9], hopes to join the search late in O3 [9].

Periods of commissioning typically involve painstaking troubleshooting to: understand the existing noise performance; fix un-anticipated noise couplings and cross contamination; repair damaged components; tune the subsystems towards their design goals; and maintain the facilities. Australian commissioners are on-site actively engaged in these activities. LIGO and Virgo plan the commissioning and observing runs to optimize productivity and the growth of the field (see [10]).

The current commissioning period is a little different and is particularly poignant for me. Following great success in the development of a quantum optical process known as squeezing [11,12], LIGO and Virgo made the decision to install squeezers on their advanced detectors

during the 2018 commissioning period. This is the culmination of a major focus and goal of my research activity. The development of squeezers for specific use in gravitational wave detectors was pioneered in my group at the Australian National University over the last 14 years.

What is squeezing? Zero-point vacuum fluctuations add fundamental noise to the amplitude and phase quadratures of a quantized light field. The Heisenberg
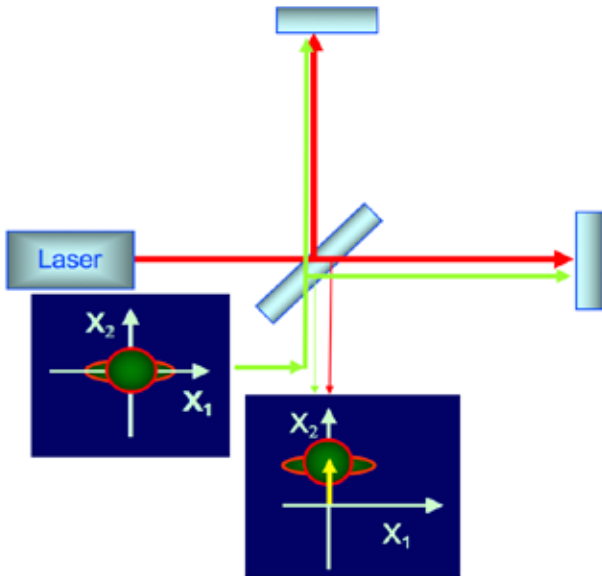
Figure 5: Simple Michelson interferometer. The interferometer is operated on a 'dark fringe' so vacuum fluctuations (green paths) couple in through the output port of the central beam splitter. Left hand dark blue box depicts the conjugate quadratures of the vacuum field entering the interferometer. Circles represent un-correlated vacuum noise. Ellipses - squeezed vacuum noise. The right hand dark blue box graphically depicts the improvement in signal-to-noise when the injected vacuum field (circle) is replaced with a squeezed vacuum (ellipse)

Uncertainty Principle (HUP) tells us that the product of the (appropriately scaled) conjugate amplitude quadrature noise and phase quadrature noise has to be greater than or equal to Planck's constant. It is these quantum fluctuations entering through the outport of the main beamsplitter (see Figure 5; X1 X2 noise circles/ellipses) that is responsible for quantum noise in a laser interferometer type GW detector [13]. aLIGO is currently limited by quantum noise above about 400 Hz (see Figure 2). The signals we are searching for appear in the difference between the phase of the light leaving one arm of the interferometer and the light leaving the other arm (See Figure 5). A passing gravitational wave differentially modulates the interferometer armlengths. After removing all classical disturbances, it is the

vacuum phase fluctuations that limit how well we can resolve two phasors and thus how small a signal we can observe. This manifestation of quantum noise is commonly referred to as shot noise (SN). But vacuum fluctuations beating against the carrier light field in the interferometer arms can also randomly disturb the mirror positions, potentially obscuring the effect of passing gravitational waves. This is known as quantum radiation pressure noise (QRPN). Fortunately, QRPN and SN appear as limiting noise sources in different frequency bands [14].

Squeezing is a technique where a phase dependent nonlinear optical device, such as an Optical Parametric Oscillator, transfers noise out of one quadrature (eg phase) to the other quadrature (amplitude), without violating the HUP [12-14]. A noise circle becomes squeezed into a noise ellipse (see Figure 5). In so doing it allows us to achieve a higher phase resolution and thus observe weaker signals (Figure 5 X1 X2 noise ellipses). By tuning the angle of the squeeze ellipse with modulation frequency, quantum noise can be reduced across the bands, be it QRPN or SN or a combination [14].
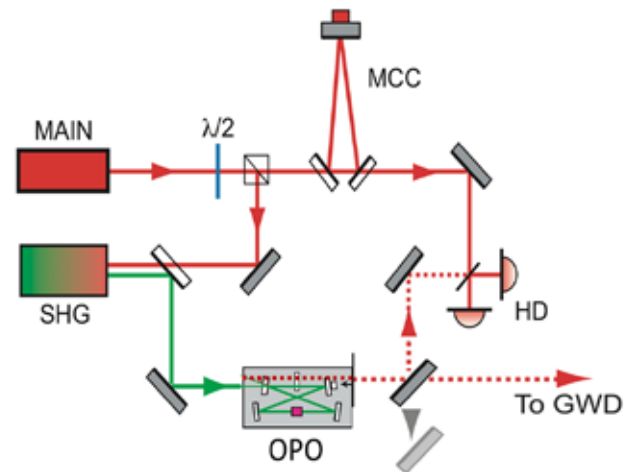
Figure 6: Schematic of a squeezed state generator using optical parametric oscillation. A Nd:YAG laser operating at 1064 nm (red beam) provided a beam which was frequency doubled in the second harmonic generator (SHG) and used as the pump (green beam) for the optical parametric oscillator (OPO). A small amount of the laser power was passed through a mode-cleaner cavity (MCC) and used as the local oscillator beam for the homodyne detection (HD) system. The OPO was operated unseeded, below threshold such that a squeezed vacuum state was produced. This squeezed state, dotted red beam, is either measured on the homodyne detection system or directed in to the gravitational wave detector (GWD).
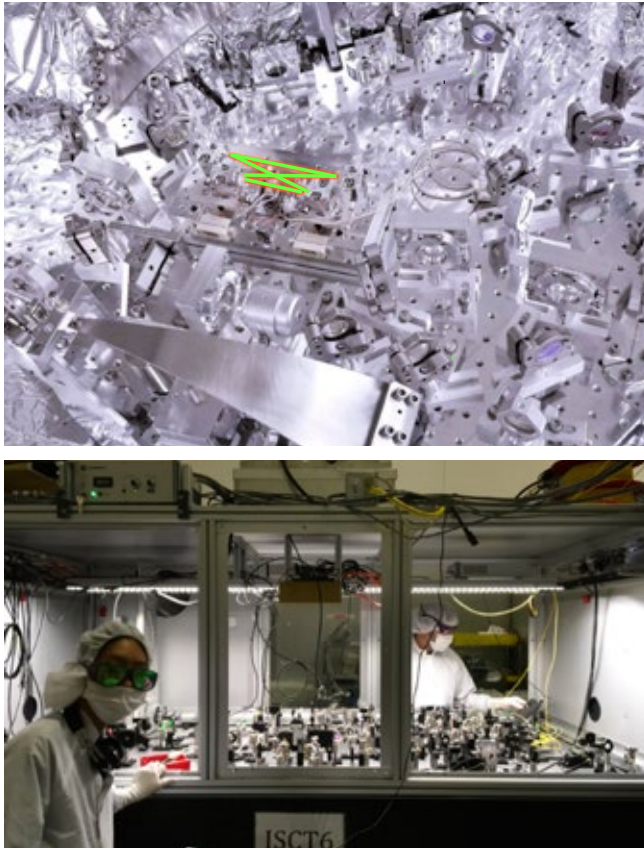
Figure 7: (a) Photograph of the ANU/MIT squeezer and components mounted on a suspended breadboard ready for insertion into the LIGO vacuum chambers. The 'green bowtie' shows the position of the OPO squeezing cavity. (b) ANU's Nutsinee Kijbunchoo and Terry McRae on-site at LIGO Hanford during squeezer installation

Squeezing was first produced by Slusher et al [15] in 1985 using four wave mixing – 0.5 dB was observed at 100MHz modulation frequencies. Not long after, Wu et al [16] produced squeezing via Optical Parametric Oscillation (OPO) also at MHz. By 1999, state of the art was 7dB in the MHz band [17]. However, gravitational wave detectors need squeezing from 10 Hz to 10 kHz, - audioband, not MHz!! In a major breakthrough we produced audioband squeezing in 2004 [18]. But it took another 8 years before we could routinely observe squeezing from 10 Hz, with the squeezed quadrature 10 times smaller (10 dB) than the un-squeezed noise [19]. Figure 6 is a schematic of the novel ANU travelling wave, doubly resonant 'bowtie' squeezer used for this work.

In 2011, with Mavalvala's group at the Massachusetts Institute of Technology (MIT) and Schnabel's group at the Albert Einstein Institute (AEI) Hannover, we demonstrated that squeezing could be applied to LIGO [20]. This proved that we needed a squeezer that could operate in high vacuum inside the LIGO vacuum envelope, and we achieved this in 2015 [21] paving that way for early adoption of squeezing in aLIGO. In a

close collaboration between the LIGO Lab (MIT and LIGO sites) and ANU, we designed, tested and built the squeezers for aLIGO [22] and installed (see Figure 7) and commissioned squeezers at both LIGO sites this year (2018), in preparation for the third observing run O3. We set a modest goal for squeezed enhancement of a factor of 1.4 at shot noise limited frequencies above 300 Hz, see Figure 2, cyan curve), which would be equivalent to doubling the laser power. In parallel with this, Virgo is installing a squeezed state generator built by AEI. We are waiting with great anticipation for the next observing run, commencing in early 2019 and scheduled to run for at least 1 year. However, this is just the beginning. Once again, we have entered into partnership with USA and the UK to implement an upgrade to aLIGO, called A+. The goal is to observe binary neutron stars out to 325 Mpc and the fiducial binary black hole systems out to 2560 Mpc.

Looking further into the future, the global community has commenced planning for new facilities to house detectors at least ten times more sensitive than the advanced detectors [24], pushing down to below 10Hz and up to a few kHz. Such detectors can potentially observe every compact binary system in the entire universe, measure cosmological parameters to 1%, measure the equation of state of nuclear material, probe the limits of general relativity and, most exciting, discover brand new objects on the warped-side of the universe.

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About the author

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Superconducting circuits: designing quantum computers and flux capacitors

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Superconductivity, the flow of current without dissipation at sufficiently low temperatures, is one of the most surprising properties of metals. Even more surprising is that when two pieces of superconducting metal are separated by an ultra-thin region of insulator, their current and voltage characteristics depend on the quantum mechanical phase of the superconducting state itself. This relationship between the quantum mechanical behaviour and the electrical response of a circuit underpins magnetic field detectors, quantum computer components, and devices for high precision electrical standards. However, important questions still remain around how we can improve these devices, increase their reliability, reduce noise and improve performance.

Superconductivity and tunnelling

When current flows through a metal wire, the wire gets hot. This seems to be an obvious statement. The effect makes electric stoves and heaters work, incandescent globes shine and the water in kettles boil – we see it every day. The reason for the wires getting hot is that the electrons travelling through the metal experience *resistance*, due to collisions with the atoms in the metal. A slightly less trivial statement is that as you cool a metal, the resistance decreases. In fact, at low temperatures the resistance typically scales as $\rho \propto T^5$.

If this were the end of the story, this would be a very short article. However, something far more interesting happens for some materials, at very low temperatures (see Figure 1). The resistance suddenly drops to zero and the metal becomes a *superconductor*. Although this effect was first observed experimentally in 1911 [1], it took until 1957 to develop a fully quantitative theory of how the superconducting state forms [2]. The resulting theoretical description, known as Bardeen-Cooper-Schrieffer (BCS) theory, is based on the idea that the electrons interact via phonons in the lattice. The electrons "pair up" forming a composite particle which we refer to as a Cooper-pair. It is these Cooper-pairs which flow through the material and result in current flow without dissipation, i.e. zero resistance.

One interesting result of this dissipation-less state is that superconductors expel any applied magnetic field, which is referred to as the Meissner effect [3]. This is because the dissipation-less current can flow to completely screen any magnetic field entering the superconductor (up to some critical magnetic field which depends on the material).

The resulting force applied to the source of the magnetic field is the principle underpinning magnetic levitation in high speed trains, open-day physics demonstrations and YouTube videos of liquid nitrogen powered hoverboards.
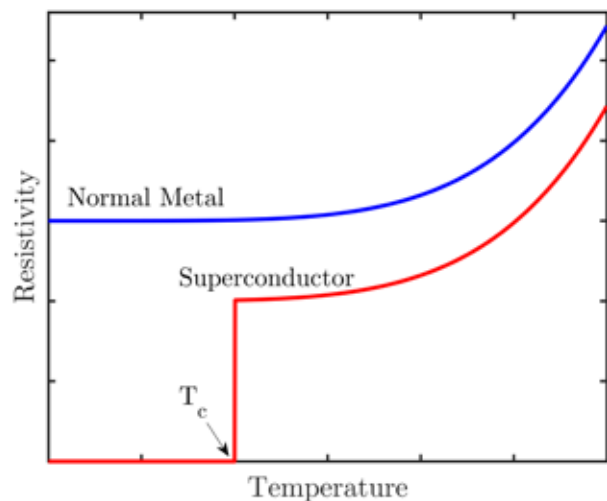
Figure 1: Typical resistivity as a function of temperature for a normal metal and a superconductor. The resistivity of the superconductor suddenly drops to zero at the critical temperature T_c.

Another effect, which is particularly important in nanoelectronics, is quantum tunnelling. The idea that particles can "tunnel" through a potential barrier is one of the well-known results from quantum theory and is also observed for Cooper-pairs. If two regions of a superconducting material are separated by a narrow non-superconducting region (often an insulator), the Cooper-pairs can tunnel from one superconducting region to the other. The equations that govern this "Josephson effect" [4] are particularly interesting. They constitute two fundamental observations. Firstly, the current

flowing through the insulating region (or "Josephson junction") depends on the critical current (I_c) which in turn depends on the characteristics of both, the junction and the superconductor. The current also depends on the phase difference $\Delta\phi$ between the wavefunctions of the superconducting state in each metallic region. The resulting expression

$$I(t) = I_c \sin\Delta\phi(t) \quad (1),$$

relates the current to the phase difference, but not the voltage across the junction. In other words, this relationship does not follow Ohm's law. If a voltage is applied across the junction, a second relationship comes into play:

$$V(t) = \frac{\hbar}{2e} \frac{\partial\Delta\phi(t)}{\partial t} \quad (2).$$

This is the second Josephson relation and again shows a quantum mechanical connection between a macroscopic variable (the voltage) and the phase of the superconducting wavefunction. Through the Josephson effects, these equations connect variables we can measure and manipulate (current, voltage) with the quantum mechanical state of the circuit, resulting in what's known as a macroscopic quantum phenomenon.

Quantum circuits

The Josephson effect finds its way into many existing technologies. Circuits containing Josephson junctions can be found in devices used to image the minute magnetic fields generated by the brain (a technique known as magnetoencephalography [5]), in mineral detection apparati used by the mining industry to discover and map ore bodies [6], and in the fundamental connection between the SI units of frequency and voltage which underpins international electrical standards [7]. Yet, in all these applications the circuit is operating in what is known as the "semiclassical" regime. Essentially, the Josephson junction is acting as a large non-linear circuit element, in contrast to the usual linear circuit elements such as capacitors and inductors.

The use of superconducting circuits in the semiclassical regime for magnetic field sensors is now technological mainstream [8]. However, we are currently in the throes of a new technological revolution. This is sometimes referred to as the "second quantum revolution" or the rise of quantum technology and quantum engineering [9]. The aim is to use quantum coherence and ultimately quantum entanglement to design new types of

technology for applications in computing, sensing and secure communication, to name a few. In order to do this, it is important to *isolate* a quantum system from its environment. In practice, this requires designing a device which is decoupled from all the thermal, electrical, magnetic and vibrational fluctuations which make up the cacophony of the world around us. All of this random noise causes our circuit to behave in a less quantum way, inducing a process known as "decoherence". Only when all these random fluctuations can be minimised or eliminated can our device display true quantum coherent behaviour. Once this limit is reached, we can start to reap the benefits of enhanced sensing or computational power.

It turns out that superconducting circuits are an ideal platform to design devices which are truly quantum coherent. The superconducting state is dissipation-less, the Meissner effect helps exclude stray magnetic fields, and ultra-small circuits can be designed with characteristic energies much greater than thermal noise at temperatures below 1 Kelvin. Despite technological challenges, reaching those ultra-cold conditions is becoming more routine. The advent of modern (closed-cycle) dilution refrigerators has made it possible to operate devices at temperatures of 10-20 mK without all the messy refilling of liquid helium which was the bane of many a PhD student working on superconductivity in previous decades.

Quantum Computers

There is currently a world-wide race to build a large scale, high fidelity quantum computer. The promise of simulating complex quantum chemistry problems or cracking cryptographic keys has unlocked investment at a scale, and focused the scientific community in a way, that is rarely seen. At a more fundamental level, being able to control many millions or billions of quantum bits (qubits) in a computer is an incredible engineering challenge. To also use quantum assisted error correction with sufficiently high precision to correct the errors inevitably creeping into the computation seems almost impossible.

Yet, the ideas and necessary technology have more recently advanced far enough to not be merely academic efforts but to be taken seriously by the commercial world [10]. Major IT companies like Google, IBM and Microsoft now drive large-scale experimental efforts around quantum computing (see Figure 2 for an example from the IBM team [11]) as well as hosting purely theoretical research groups. There is also a raft of

privately funded start-ups as well, all based on one of a number of different technologies which have progressed beyond simple proof-of-principle demonstrations.

Superconducting circuits are one of the leading technologies in this race. The ability to fabricate electronic circuits, which initialise, manipulate and read out a quantum state, is at the heart of what is required for a quantum computer. Much of the required control electronics for these circuits already existed (albeit in a simpler form) in semiclassical applications of Josephson junctions. However, maintaining coherence of the quantum state is a tricky business, no matter which platform you choose. Microscopic fluctuations in the local magnetic field, in the charge on the surface of the chip, in the control voltages and even the infrared photons trapped in the refrigerator can all lead to decoherence. Therefore, the race is on to develop new designs, new fabrication techniques, and new architectures which result in better performance, faster gates and lower noise. It is far from clear that superconducting circuits will ultimately be the best solution to these problems, but they are certainly leading the charge.
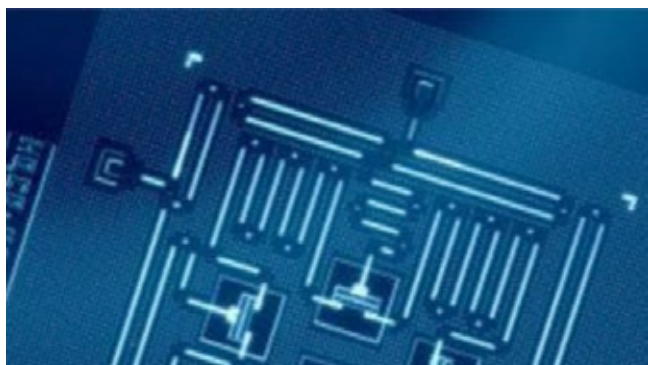
Figure 2: A device consisting of four transmon qubits, four quantum busses, and four readout resonators fabricated by IBM and published in NPJ Quantum Information in January 2017 [11].

Engineering better qubits

One of the key problems with superconducting quantum computer designs is the use of metal-oxides. The Josephson junctions themselves are comprised of 1-2 mm thick oxide layers, while the entire circuit is typically also covered in a native oxide layer of a few nanometres. The problem is that this oxide is an amorphous material, which means that the atoms display a large amount of randomness in their placement (they are in a glass-like state). This is in stark contrast to the atomically precise single-crystal silicon which is used to produce modern microelectronics.

The inclusion of glassy metal-oxide in the design of quantum computers in turn introduces a problem which has puzzled solid-state physicists for decades. Amorphous materials in general contain defects, typically bistable defects, formed due to the amorphous nature of the material itself. If these materials are then used to produce electrical circuits, these defects provide a loss channel to the circuit, limiting its performance. However, we are still not sure about exactly what causes these defects or how to eliminate them. This is also true for quantum computing components, but now the circuits are many times more sensitive to these random defects. In fact, qubits have proven to be an exceptionally good probe of the nature of defects in amorphous materials and we have recently used them to gain new insight into this decades-old problem [12].

There are other significant challenges in creating a noise-free environment for these sensitive circuits. Any voltage or current fluctuations in the room temperature control electronics can be transmitted down to the coldest parts of the fridge, where they correspond to an effective noise temperature well above acceptable limits. Those same wires, which connect to the control electronics, can suffer from "cross-talk" where a signal on one line can induce parasitic signals in the other lines. Imperfections can be caused by adsorbed impurities on the chip surface, parasitic resonances between the nanoscale components, temporal and spatial variation which cause the circuits to drift away from their calibrated operating points. This parameter drift means that the circuit has to be recalibrated at regular intervals to ensure optimal performance – an increasing problem as the circuit complexity increases. All of these complications and more need to be addressed in order to produce high fidelity quantum operations with low noise on timescales that are useful for quantum technology applications.
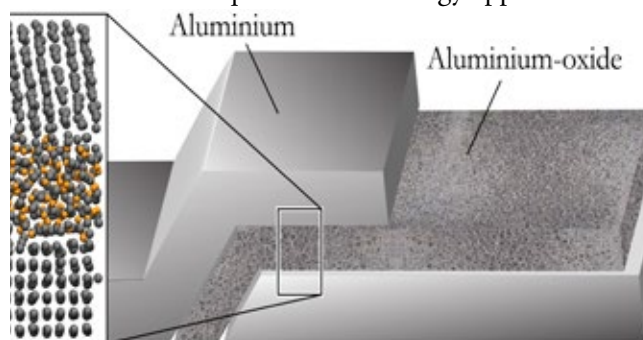
Figure 3: A typical Josephson junction is comprised of a layer of aluminium deposited on top of a few nanometre thin aluminium oxide layer. The insert shows an atomic model of this interface [13].

There is still extensive research going on to track down each and every source of noise and drift in these circuits and eliminate them one by one. Our research is developing computational models of the fabrication process, of potential defect candidate models and of the devices' electrical characteristics. Figure 3 shows an atomic scale model [13] of the aluminium-oxide junction within a quantum circuit. By developing better computational models, we can improve the fabrication process and ultimately the performance of quantum computers and nanoelectronics devices in general.

Duality in quantum circuits

One of the most interesting aspects of working with superconducting circuits is that the effective Hamiltonian of the system depends on the choice of circuit components and topology. Depending on how capacitors, inductors and Josephson junctions are wired together, a vast array of different symmetries and devices are possible. This is particularly interesting as circuits can be constructed to mimic many well-known models from quantum optics, condensed matter physics and other branches of physics, many of which do not yet have an exact (or even approximate) solution. By mapping from an unknown model to a known model, we can learn more about both the effective (circuit) version of the model, as well as the original problem.

When moving from an electronic circuit diagram to the Hamiltonian of an effective model, a key concept is the idea of conjugate variables. We are typically familiar with this concept from introductory quantum theory, where the position and momentum of a particle cannot be simultaneously determined with arbitrary precision. In quantum circuits, a similar relationship exists between charge and magnetic flux. For example, a simple ring of superconducting metal can only contain an integer multiple of the superconducting magnetic flux quanta ($\Phi_0 \approx 2.068 \times 10^{-15}$ Wb), while the current carrying Cooper-pairs are completely delocalised around the ring. In contrast, in a circuit including a region of metal with dimensions of only 10's-100's of nanometres, the small self-capacitance of the island will result in a large charging energy. This in turn means that the number of charges on the island is well defined, but the corresponding phase or flux variable will be delocalised. The correspondence between phase and flux can be expressed mathematically as:

$$[\hat{\phi}, \hat{q}] = i\hbar \quad (3),$$

where $\hat{\phi}$ and $\hat{q}$ are the operators corresponding to flux and charge respectively. From this expression, many of the standard results from quantum theory follow directly.

This correspondence is also part of a deeper duality between flux and charge. A familiar version of this duality is well known from conventional circuit theory. The use of Thévenin and Norton equivalent circuits is a standard technique to convert between circuit models involving voltage and current sources. It turns out that this is part of a much deeper concept. The full quantum circuit duality involves interchanging voltage and current sources, capacitors and inductors, impedances for admittances etc. [14].

At this point, the obvious question to ask might be what is the dual component to a Josephson junction.
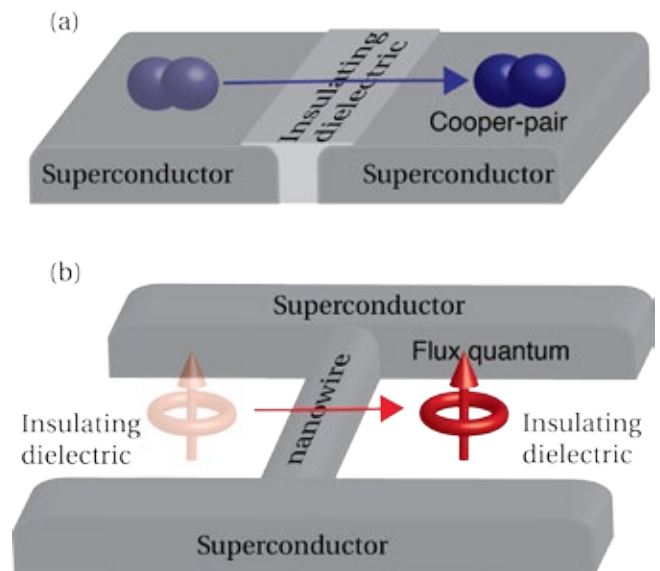
Figure 4: (a) A Josephson junction is a thin insulating barrier between two regions of superconductor, through which Cooper-pairs can tunnel. (b) Two regions of superconducting material connected via a nanoscale constriction forms a barrier for magnetic flux quanta. This is a quantum phase slip element and is the dual of a Josephson junction.

This question is actually a little complicated as the Josephson junction is actually self-dual, under the correct transformations. However, a more interesting answer has recently become the focus of study. The dual component is called a "quantum phase slip element". This element consists of a narrow but continuous region of superconductor (a nanowire). Due to the Meissner effect, the nanowire forms a barrier for magnetic flux to tunnel across the wire. However, given the correct circuit parameters, magnetic flux can tunnel through the barrier in a completely analogous way to Cooper-

pairs tunnelling through a Josephson junction. Figure 4 illustrates this duality between Josephson junctions and quantum phase slip elements.

The great promise of quantum phase slip elements is that new circuit designs could be possible, comprised entirely of metallic nanostructures. This would remove the need for the metallic oxides which seem to cause us so much trouble in Josephson junctions. However, the typical materials of choice for quantum phase slip elements are disordered two-dimensional superconducting films which come with their own materials science challenges. Much is still to be understood about both the fabrication and design of such devices, but progress is being made [15, 16].

### Circulators and Flux-capacitors

Another key problem in building and controlling quantum circuits is the problem of electrical isolation. In an ideal quantum circuit running at low temperatures, the control pulses should go into the circuit, and the measurement signal should come out. However, the electrical noise on the input pulses is often much larger than the measurement signal coming out. This problem is typically dealt with via a device called a circulator. A circulator is a three-terminal device which behaves like a roundabout where every vehicle must follow the GPS instruction "take the first exit". Because each vehicle (or in this case electrical signal) always exits the next available port around the circle, this device is non-reciprocal. This is an example of local time-reversal symmetry breaking. If all the directions of the signals are reversed, the paths are not simply reversed – the direction of the round-about continues as before and the signals still leave the circle at "the first exit".

Circulators in modern superconducting circuits are still bulky devices compared to the rest of the circuit, a few tens of millimetres in size. Because introducing a local magnetic field is one of the simplest ways to break time-reversal symmetry locally, they also typically contain some ferromagnetic material which makes them relatively incompatible with the rest of the superconducting circuitry. Therefore, there is a strong need for an 'on-chip' circulator which can be integrated into existing quantum technology.

We recently studied a new type of on-chip circulator based on a ring of Josephson junctions (see Figure 5). Simplifying an existing design [17] and using a new mathematical approach, we were able to show that using realistic parameters an on-chip circulator was

possible which had performance characteristics similar to existing devices [18] while using standard fabrication techniques. In addition, thanks to the charge-flux duality discussed in the previous section, we also showed that an equivalent design was possible using quantum phase slip elements with similar performance. In our Josephson junction based device, charges move around the ring which is biased via an inductive loop. In the QPS design, fluxes move around a ring biased by a capacitor. The fact that the latter circuit also looked like the flux-capacitor from Back to the Future was a convenient selling point for social media!

The future of quantum circuits
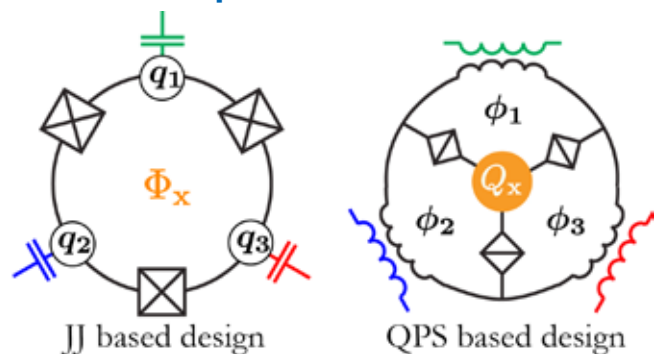
Figure 5: Designs for an on-chip circulator, based on either Josephson Junction (JJ), or Quantum Phase Slip (QPS) elements [18]. The circuits are equivalent under the charge/flux duality, however their sensitivity to noise and fabrication variation are different.

Over the past four decades, superconducting circuits have been a fruitful playground, both from a fundamental science point of view, and in terms of developing new technologies. However, in the last 10-15 years we have moved into entirely new territory, that of fully coherent quantum circuits. The ability to directly initialise, manipulate and readout a quantum state using relatively standard electronics equipment opens up an entirely new world of possibilities. The technology finds application in everything from building a full scale coherent quantum computer, to novel high precision magnetic field sensors and even superconductivity demonstrations for undergraduates [19].

While future quantum technology based on superconducting devices shows great promise, the attraction for me is still being able to take an electrical circuit, analyse its behaviour at the quantum level and then see that same behaviour measured in the lab. Deep connections between theory and experiment, between electronics and many-body physics, between classical and quantum processes, can all be found with simple combinations of electronic components and superconducting materials. Yet, these innocuous circuits

are still pushing the boundaries of what we can fabricate, simulate and understand.

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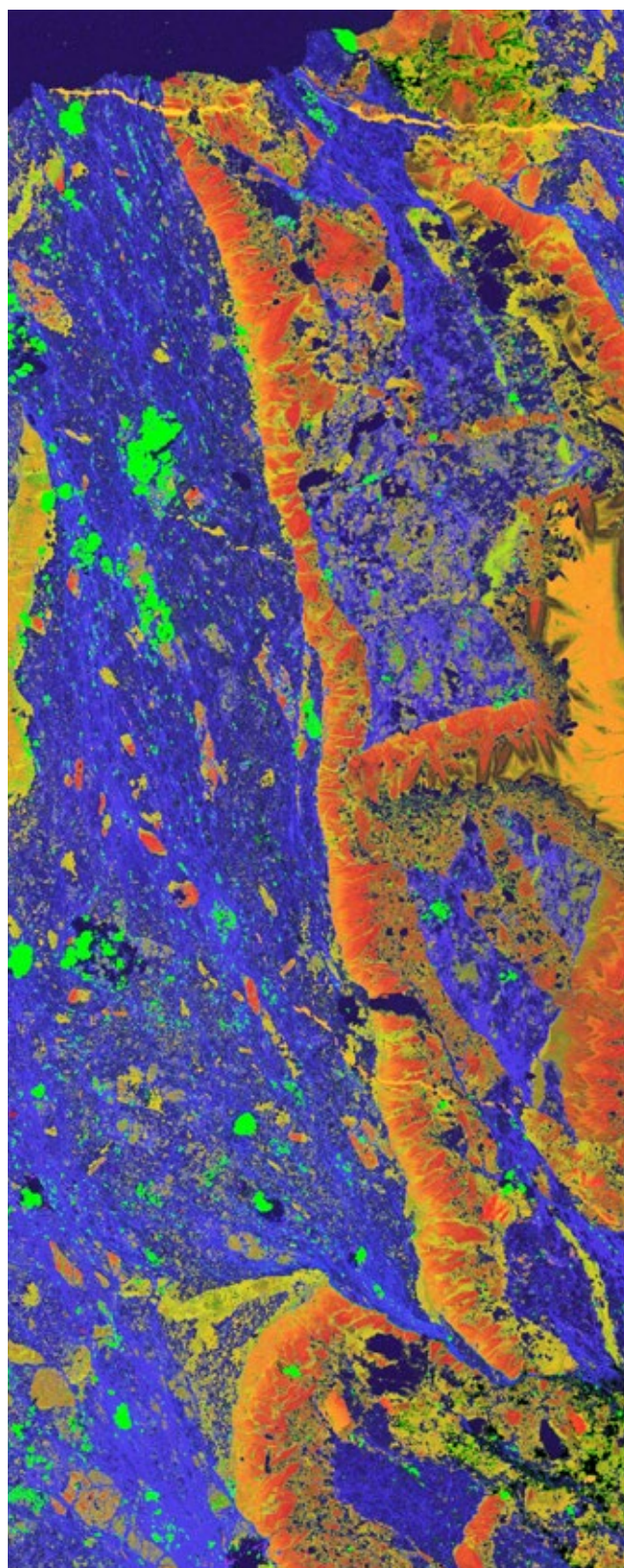
Image across a whole thin-section sample from Sunrise Dam Gold Mine (Fisher et al., Miner. Deposita 50, 665-674 (2015)), showing a gold-bearing quartz-carbonate vein; acquired at the XFM beamline, Australian Synchrotron - ANSTO, using the Maia detector system (developed by CSIRO and Brookhaven National Laboratory). Image displays Sr, Fe and Rb in RGB (cropped, original size 66,668 x 15,001 pixels, 40.0 x 9.0 mm2, 0.13 ms/pixel, 1G pixels, 250 GB).

Revision of the SI: a journey from precious artefacts to constants of nature.

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The International System of Units, Système Internationale (SI) will soon undergo a long awaited transformation. It brings to fruition a dream first voiced over a century ago by Gauss, Maxwell and Planck, of a unified system of measurement linked not to physical artefacts, or even to atomic material properties, but to immutable constants of nature. In May 2019, the remaining four base units of the SI not yet defined by constants of nature: the ampere, kilogram, kelvin and mole, will adopt new "implicit" definitions through fixing the numerical value of the electron charge and the Planck, Boltzmann and Avogadro constants. This change, made possible by recent advances in measurement science, will address long-standing concerns about the stability of the current kilogram and kelvin definitions and about the gap between the SI-definition of electrical standards and their present practical implementation.

A quest for unity

Accurate measurement has long been recognised as essential to the smooth operation of trade. Yu-the-Great first unified length measurement [1] for taxes and trade in China in 2200 BCE as part of managing his new empire. Empires from the Romans to the British also sought to standardise measurement: the Magna-Carta [2] stating "*There shall be standard measures… throughout the kingdom*". The roots of our current SI lie with the metric system adopted by the French Revolutionary Government in 1795 in the midst of the French revolution.

By the mid-1800s many countries had already adopted the "metric" system. However it was not until 1875 that the Metre Convention, one of the very first international treaties, was signed by representatives of 17 of the major industrial economies of the time (Australia signed in 1947). This established internationally agreed standards of length and mass, defining the metre and the kilogram.

> *"The SI is so familiar to physicists that it is like the air we breathe: essential, almost invisible to us, and hard to imagine what life would be like without it."*

With the advance of science in the 19th century, it was recognised that scientific and engineering progress requires a uniform language for the communication and comparison of results, and the development of agreed standards. Lord Kelvin observed [3] that "*if you cannot express something in numbers, your knowledge is of a meagre and unsatisfactory kind*". As physics developed, many relationships between both physical and electromagnetic quantities were established. Physicists such as Gauss, Weber, Maxwell and Thompson observed that the units used to measure these quantities could be reduced to a small subset, leading first to the cgs, then MKS, MKSA and finally our present SI [4] comprising the seven familiar base units from which all other units may be derived.

Why revise the SI?

Firstly, the unstable kilogram: In 1889, Johnson-Matthey fabricated a new Pt-Ir kilogram reference, "big-K" and four (and shortly later, 2 more) identical copies for the *Bureau International des Poids et Mesures* (BIPM), the international body located at Sevres near Paris to maintain the metre-treaty standards. In 1946 big-K was again compared to these copies, and it appeared that the relative masses of the copies were changing [5]. Was *big-K* really constant? Or was it also subject to the same processes causing the apparent change in its 6 copies? Another comparison in 1991 suggested that *big-K* was probably losing weight at the rate of about 1 µg per year. The effects of the cleaning process on its adsorbed hydrocarbon and water surface layers [6], and potential contamination from atmospheric mercury [7] have been implicated, but no definitive process has been identified. Although *just* manageable for the moment (1 kg masses are calibrated for industry at the NMI with an uncertainty of 50 µg), in the longer term this will be a problem for trade and industry. For example, the pharmaceutical industry now regularly requires analytical balance calibrations at the microgram level.

"Big K", a Pt-Ir cylinder 39 mm in diameter and height, kept in a safe in the _Pavillon de Breteuil_ near Paris — and defining mass throughout the universe!

The second issue with the SI is the impracticality of the present definition of the ampere, which underpins all the electromagnetic measurement units including voltage, resistance and magnetic field strength. The SI defines the ampere as the current generating a force of 2×107 N/m between two infinite wires spaced 1 metre apart. Using this definition, the ampere can only be experimentally realised with an accuracy of a few parts in 10^7.

The Nobel Prize winning discoveries by Josephson [8] of quantised voltage steps of $h f/2e$ in superconducting tunnel junctions in the 1960s, and by von Klitzing [9] of quantised resistance steps of $h/e2$ in quasi-2D semiconductors in 1980, offered reproducibility over a hundred times better. Responding to industry demand
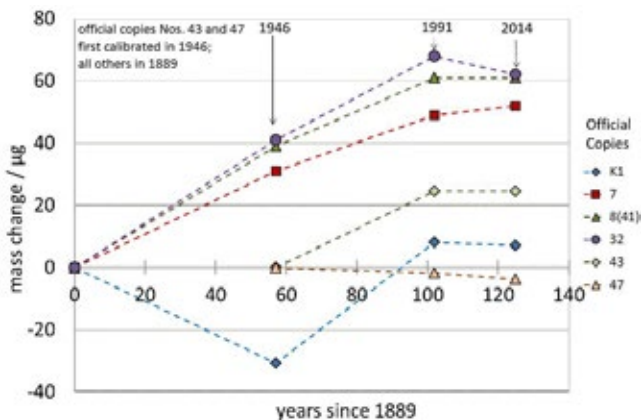
Comparisons of _big-K_ with its copies, showing both the drift and instability of Pt-Ir masses disseminating the SI kilogram.

for greater accuracy, in 1990 electrical metrologists adopted a separate system of "conventional units" based on the adoption of fixed "conventional values" for the Josephson and von Klitzing constants [10, 11]. It was a practical solution, but not strictly coherent with the SI.

Finally, the SI unit for temperature, the kelvin, is presently defined as one 273.16th of the temperature of the triple point of water, the temperature at which the three phases of water are in equilibrium. Although in principle a universal definition — after all, water is the same across the universe — this definition has already caused problems. In 2006, a comparison [12] between national laboratories across the world showed differences of up to 0.1 mK that were not explained by the estimated uncertainties. This is a small effect, but laboratories like CSIRO's facility for the calibration of deep-ocean monitoring buoys require 0.1 mK-level NMI calibration of their references. In response to international need for accuracy, the SI definition was amended in 2011 to more tightly specify the isotopic composition of the water used. Although not imperilling key long term data sets such as global temperature, it was a worryingly close call, and a salient warning about the risks of standards based on physical systems.

The upcoming revision of the SI [13] is designed to address these issues whilst carefully maintaining both continuity of standards and calibration uncertainties for scientific and industrial communities.

A journey from artefacts to constants

The history of measurement standards has been a multi-millennia story of the search for absolutes. Most recently, in 1793, in the midst of the French revolution, the new government announced it wanted to establish measurement units that were "_accessible to all people for all times_", and not connected with any physical artefacts of the state. The metre was defined as one ten-millionth of the distance from the equator to the pole; the _grave_ (later to be re-named the kilogram) as the mass of a cubic decimetre of pure water at its freezing point. Unfortunately, it soon became clear that the difficulty in realising these new definitions was great: the surveyors contracted to triangulate the meridian to realise the metre took years to complete their task, and the accuracy achieved for both units was unable to satisfy the demands of science, industry and trade. In 1799 universality was compromised for commercial reality and a Pt mass and Pt metre bar were fabricated to provide useful working standards.

However, physicists such as Gauss still pined for artefact-free standards. In 1870 Maxwell stated [14]: *"If we wish to obtain standards of length, time and mass which shall be absolutely permanent, we must seek them not in the dimensions, or motions or mass of our planet, but in the wavelength, the period of vibration and absolute mass of these impenetrable and perfectly similar molecules"*.

In 1900, Planck [15] went further *"... with the help of fundamental constants we have the possibility of establishing units of length, time, mass, and temperature, which necessarily retain their significance for all cultures, even unearthly and nonhuman ones."*

Some of our base units have already completed Maxwell and Planck's journey. The metre had taken the initial step away from an arbitrarily defined metal bar to the more universal "fraction of the size of the earth", but due to practicality stepped back again to a metre bar. However, advances in atomic physics and interferometry facilitated a significant increase in accuracy and a step towards universality when in 1960 the metre was redefined in terms of the wavelengths of the ^{86}Kr atomic emission line. In 1983 [16], the extraordinary accuracy with which the standard of time could be established through the microwave transition of a caesium atom, better than parts in 10^{12}, facilitated the metre's final step. The metre is now defined by the distance light travels in exactly one 299,792,458th of a second. By *assigning* an exact fixed numerical value to the speed of light, the metre is implicitly defining through the SI-second. This approach sets the scene for the upcoming revisions to the definitions for the kilogram, kelvin and the mole.

A quantum kilogram

The rationale for the "backward step" that took the unit of mass from a material property (the density of water) back to a physical artefact remained relevant up until recently. Many techniques were proposed for "counting atoms" to units based on Maxwell's *"perfectly similar molecules"*, such as accumulating a known mass through electrolytic or ion-beam deposition. Unfortunately, the proposed replacements could not achieve an uncertainty sufficiently low to meet the demands of industry.

In the 1990s, the semiconductor industry's ability to grow near-perfect crystals of silicon provided a potential solution. Researchers at CSIRO polished crystals of isotopically pure silicon [17], sourced from unique facilities in Russia, to near perfect spheres whose diameter could be measured to the level of a single

CSIRO scientist Katie Green inspecting a silicon sphere used in experiments to measure the Planck constant by relating the macroscopic SI mass units to atomic masses (photo: CSIRO, 2007).

atomic layer using interferometry. Together with unique capabilities in Italy to measure the lattice spacing using X-ray diffraction, linked to the SI metre using laser interferometry, it was possible to determine the exact number of atoms in the sphere and relate the atomic mass to macroscopic mass scales.

Researchers at Australia's National Measurement Institute (NMI) were involved in the first phase of this project, making mass and diameter measurements [18] of the first spheres. Researchers at ANSTO's OPAL reactor are still involved in the project, using their unique capabilities to quantify impurities in the silicon at the subppb level using neutron activation spectroscopy. Many confounding factors and corrections, such as multiple types of oxide-layers on surface of the spheres, and the need to determine temperatures at the mK level to correct for thermal expansion, needed to be overcome to achieve the current uncertainty of a few parts in 10^8 [19] in relating atomic mass to the present SI kilogram.

A second technique, the "watt-balance" [20], adopted different physical principles to related mass to the electrical units for power. Recently renamed the "Kibble balance" in honour of Brian Kibble, who championed the concept, it uses the force $F = B\,i\,l$ generated by a current, i, through a coil of length l in a magnetic field of flux density B to balance the weight of a reference mass. Slowly oscillating the coil to generate a voltage $V = B\,v\,l$ allows determination of the geometric factor $B\,l$ associated with the coil and magnetic field (integrated appropriately to account for magnetic field non-uniformity). Current and voltage measurements are made in terms of the quantum-Hall and Josephson effects (and not the present SI units) whilst laser interferometry is used to measure the velocity of the moving coil in terms of the second and the speed of light. Experiments in the US, Canada [21] and others have now achieved accuracies of 20 parts per billion.

Although these two experiments seem to offer very different approaches to the definition of the kilogram, they both relate the unit of mass directly to the Planck constant h: in the Kibble balance through the von-Klitzing and Josephson constants and for the Silicon sphere through the revised-SI's Avogadro constant (see later). A key condition set by mass metrologists before the SI revision could occur was that these two very different approaches should agree within their uncertainties, a condition that has now been met. The new definition of mass in terms of the Planck constant links two of physics most important equations: Einstein's mass-energy equivalence, $E = m\,c^2$, and Planck's expression for the energy of a photon with frequency f, $E = h\,f$. In the present SI, the experiments above *measure* the Planck constant, whilst in the proposed revision, the adoption of a fixed value for the Planck constant, determines the unit of mass.

Due to the difficulty and complexity of the Planck constant measurements, most national laboratories will not routinely realise a mass scales in terms of Plank's constant. Instead, the BIPM will replace *big K* by an ensemble of reference masses, taking advantage of new experimental results as they become available from labs around the world.

One consequence of the revision for mass metrologists is that the SI kilogram will take on the uncertainties in the Sphere and Kibble experiments, rather than its present uncertainty of zero. Although small, probably 20 to 30 µg, it will have potential flow-on effects to users with

NMI scientist Kitty Fen comparing a stainless steel E0-level 1 kg mass withone of Australia's two Pt-Ir kg references at the microgram level, in a pressure controlled chamber at the NMI.

the most demanding applications. NMI is mitigating this by reducing the uncertainties elsewhere in the chain of calibration. For example by reducing the present 10 µg uncertainty in the 120 mg buoyancy correction associated with the density difference between Pt-Ir and stainless steel kilogram masses.

Electrical units re-join the SI
In the revised SI, the electron charge, e, and Planck's constant, h, will no longer be measured in terms of the SI kilogram and ampere units, but will adopt fixed values, allowing the volt and ohm to achieve parts in 10^{10} accuracy based on the Josephson and quantum-Hall effects. The ampere can then be generated from these units.

The adoption of an exact value for the electron change also enables a direct realisation of a standard for current in terms of frequency (i.e. the SI second) through newly developed single electron pump technologies [22]. This facilitates a valuable cross check on the Josephson and von Klitzing effects, the so called quantum-triangle of measurement [23].

A new kelvin
Temperature is one of the most measured parameter in industry, due to its impact on process control and energy efficiency. Any change in its definition faces the same issues as for the kilogram: what to replace it with and when is the time right?

Boltzmann's constant, the proportionality constant between the energy and temperature, is presently measured in terms of the SI units the kelvin and watt using experiments for which the thermodynamics can

be accurately characterised. The SI revision will adopt the same approach as for the kilogram and metre, implicitly defining the size of the kelvin by fixing the value of the Boltzmann constant. Importantly, it does not specifying the system or experiment relating it to the watt and kelvin.

One promising technology is grapefruit-sized aspherical acoustic resonators [24] whose dimensions can be determined at the sub-ppm level based on microwave resonances (linked to the SI metre and second), to accurately measure the sound velocity v in a monatomic gas. Boltzmann's constant can be determined from $v^2 = \frac{5}{3} \frac{kT}{m}$ using the known molecular mass, m.

Another promising method is Johnson noise thermometry [25], using the principle that the thermal electrical noise in a resistor is given by $P = k\,T\,B$, where B is the effective electrical bandwidth of the system. Until recently this was limited by our ability to calibrate the frequency response and sensitivity of the noise voltage measurements. However, recent advances in programmable Josephson-junction arrays can now generate arbitrary high-frequency waveforms with sub-ppm quantum accuracy. Other techniques, for example ultra-high resolution spectroscopy of the thermal broadening of atomic absorption lines, are also under investigation.

Concerted efforts [26] at various laboratories around the world have, in recent years been able to measure Boltzmann's constant to just below 1 ppm: still not as good as the 0.1 ppm supplied by the current kelvin definition, but satisfactory for nearly all users. Extensive discussions within the technical committees established under the Metre Treaty decided that the benefit gained from transfer to a definition based on a fundamental constant outweighed the associated increase in uncertainty of the unit. However, as with the electrical units in the 1980s, a practical scale, the ITS-90, will continue to be used for most applications needing 0.1 mK accuracies, until the uncertainties of the Boltzmann experiments are reduced.

At NMI we plan to use the flexibility provided by the revised SI to calibrate primary radiation thermometers (a type of reference-grade thermal imaging camera). Planck's radiation law, gives the radiance L of a blackbody at temperature T in terms of wavelength λ and the constants c, h and k as $L = 2hc^2\lambda^{-5}[\exp(hc)/\lambda kT)-1]^{-1}$. NMI is developing methods measure optical radiance in terms of the SI, using both photometric [27] and
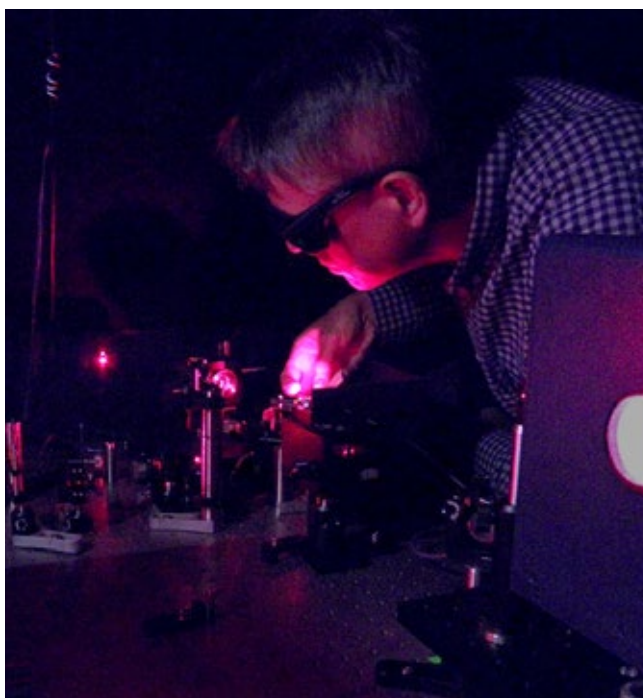
NMI is developing a tuneable Lambertian source providing known spectral radiance traceable to SI base units for the calibration of primary radiation thermometers directly in terms of the Boltzmann constant.

laser-based tuneable radiance sources [28] with sufficient accuracy to replace existing ITS-90 fixed-point cell thermometric references.

Bridging the gap between the macroscopic and atomic worlds: the mole

Physicists currently use essentially two scales for mass: one operating on the macroscopic scale (the SI kg) and one on the microscopic scale: atomic mass units (amu), defined as exactly one 12th of the mass of a ^{12}C atom. Measurements in both regimes can be made at the ppb level, however relating the two requires the use of the Avogadro constant, currently *measured* in terms of the SI mole. One mole of ^{12}C weighs *exactly* 0.012 kg, defining the mole. As with the kilogram and the kelvin, these roles will swap. The Avogadro number will become fixed rather than measured and the atomic mass of ^{12}C measured rather than defined as exactly 12 amu. The Avogadro number N_A can be expressed in terms of the molar mass M_u through $N_A = A_r(e)\,M_u\,/\,R_\infty\,h\,c\,\alpha^2$, where the relative atomic mass of the electron $A_r(e)$ is known through mass spectroscopy to 1 part in 10^{10}, the Rydberg constant $R_\yen$ to less than 1 part in 10^{11} and the fine structure constant a to 2 parts in 10^{10}. With the adoption of a fixed value for Planck's constant [h] the increased relative uncertainty in the "amu" will be less than a part in 10^9 and is expected to have negligible practical impact.

Beyond constantsThe revision of the SI finally links the base units (of all measurement) to fundamental constants of nature. By moving away from definitions based on artefacts or material properties, scientists are free to use *any* of the equations of physics to realise measurement units in terms of these constants providing a firmer foundation for further improvements in measurement. Past improvements in standards have facilitated major technological innovations, such as the ubiquitous GPS system, which is underpinned by nanosecond-level timing standards. It seems almost certain that the revised SI will facilitate further innovation.

About the author

Dr Ballico completed a PhD in Plasma Physics at the University of Sydney in 1990, and worked as a postdoc in Japan, Germany and the US on thermonuclear fusion. Since 1993 he worked at CSIRO and the NMI, developing primary measurement standards and calibration systems in Temperature and Optical Radiometry. He is currently the section manager of NMI's Mechanical, Thermal and Optical Standards section. His current research interest is using the revised SI to establish temperature standards linked directly to Boltzmann's constant.

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SAMPLINGS

China unveils plans for two new gravitational-wave missions

China has revealed plans for two space-based missions to study gravitational waves. The National Space Science Center, Chinese Academy of Sciences (CAS), announced on 4 July that the country will launch a mission in 2020 to monitor gamma-ray bursts associated with gravitational-wave events. The CAS also gave the go-ahead for a fully-fledged gravitational-wave detector to be sent into space in 2033.

Gravitational waves are distortions of space–time that occur when massive bodies, such as black holes, are accelerated. Since their first direct detection in 2015 by the Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors in Washington and Louisiana, scientists have since picked up several other events from the merger of black holes as well as neutron stars.

While scientists have the capability to detect such events, pinpointing their exact location is difficult with ground-based gravitational-wave detectors. This can be improved, however, by follow-up observations from ground- and space-based telescopes operating at various

wavelengths. Gamma rays, for example, can play a unique role in this effort. During the merger of two neutron stars, a gamma-ray burst usually happens right after the generation of gravitational waves and before X-ray, optical and radio wavelengths can be detected.

Artist's image of the Gravitational wave high-energy Electromagnetic Counterpart All-sky Monitor (Courtesy: NSSC)

"It's like when you hear a thunderstorm, you look for lightning somewhere in the sky," says Shaolin Xiong, a high-energy astrophysicist from the Institute of High Energy Physics in Beijing. "The lightning shows where the thunder is coming from". Similarly, if scientists can associate a detected gamma-ray burst to a gravitational-wave event, they will be able to tell specifically which part of the sky it is happening and carry-out follow-up observations at other wavelengths.
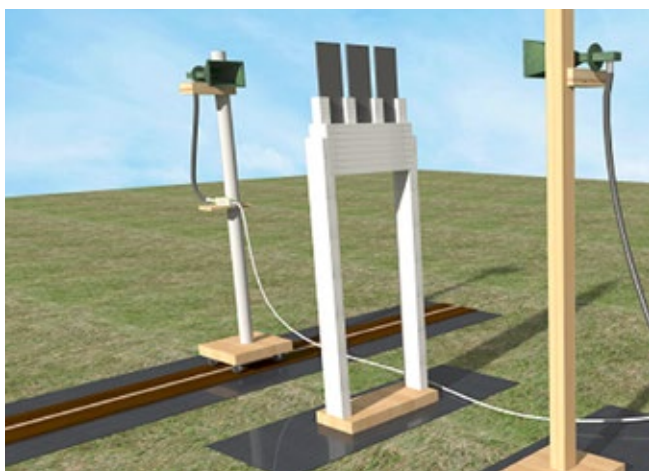
Exotic paths: artist's impression of the microwave triple-slot experiment. Courtesy: G Rengaraj et al/New Journal of Physics)

Xiong is principal investigator for a new mission that will consist of two probes placed at opposite sides of the Earth to detect gamma-ray bursts in the energy range of 8 keV – 2 MeV. Dubbed the Gravitational wave high-energy Electromagnetic Counterpart All-sky Monitor (GECAM), it is now going through "phase A" study

but the technical readiness for the mission is "high" according to Xiong. Once launched, the craft should begin operation in the second half of 2020, just when LIGO reaches its design sensitivity.

A mission to directly detect gravitational-waves from space was also given the green light for further development by CAS. Low-frequency gravitational waves are inaccessible on Earth because ground-based interferometers would be required to have impossibly long arms. A space-based mission, however, could pick up gravitational-waves with frequencies between 10–4-10–1 Hz from, for example, the coalescence of supermassive black holes.

Dubbed TAIJI, the craft would detect gravitational waves from the merger of black holes and adopt a similar mission concept and technology with the European Space Agency's LISA probe, which will launch around 2034 and consist of three spacecraft separated by 2.5 million km in a triangular formation, following Earth in its orbit around the Sun.

Like LISA, TAIJI would also place three craft in a triangular configuration in a sun-synchronous orbit with each side of the triangle instead being three million kilometers long. It will operate at a frequency range 0.01-1 Hz, and will focus on intermediate mass black-hole binaries.

Extracted with permission from an item by Ling Xin at physicsworld.com.

Exotic 'non-classical paths' affect quantum interference, experiment confirms

The importance of including exotic "non-classical paths" in analyses of quantum interference has been demonstrated experimentally by physicists in India. Urbasi Sinha and her colleagues at the Raman Research Institute in Bangalore measured the interference pattern produced by microwaves as they navigated through three parallel barriers. Their results show that the pattern cannot be calculated by simply assuming that the microwave photons travel via "classical paths" through the barriers. Instead, all possible routes through the barriers – including weaving through multiple gaps – must be accounted for.

One of the cornerstones of quantum theory is the fact that particles can also behave as waves. This can be demonstrated by the double-slit experiment, which involves firing a stream of particles such as electrons

through two adjacent slits and observing the build-up of a wave-like interference pattern on a screen on the other side of the slits. However, each particle is detected as a tiny dot within the pattern, suggesting that the particles are discrete entities too.

This double-slit pattern can be calculated by treating the system as a superposition of waves that travel through one slit and waves that travel through the other slit. However, in 1986 the Japanese physicist Haruichi Yabuki showed that this is an approximation because it ignores the tiny possibility that a particle could take a non-classical path through the slits. An example of such a path is when a particle goes through one slit and then loops back through the other slit and then back through the first towards the detector.

In 2014, a team led by Sinha used the path-integral formulation of quantum mechanics to calculate the effect of non-classical paths on the interference pattern from three slits. The calculations revealed that the deviation from a simple superposition depends on the size of the de Broglie wavelength of the particle. The

NASA's Parker Solar Probe will head seven times closer to our star than any other craft before. (Courtesy: NASA/Johns Hopkins APL/Steve Gribben)

effect is tiny for electrons and visible light – being one part in 108 and one part in 105 respectively – which is too small to detect.

However, they did show in 2014 that the deviation is much larger for microwave photons and now Sinha and colleagues have done an experiment that has measured this deviation for the first time.

Instead of using three slits, the team did a "triple slot" experiment whereby the interference pattern is created when quantum particles encounter three barriers (slots) to their propagation. Slots rather than slits were used

for practical reasons related to the size and cost of the experiment.

The team used a pyramidal horn antenna to generate a beam of microwave photons with a wavelength of 5 cm. The beam was directed at three microwave-absorbing barriers (slots) – each 10 cm wide and separated by 3 cm. A microwave detector was located behind the slots, where it can be moved very precisely to acquire the resulting interference pattern. The slots were located halfway between source and detector – which were 2.5 m apart.

The team measured a deviation of 6% from the superposition principle thereby confirming the significance of non-classical paths. They also point out that their observation has implications for radio astronomy, where arrays of detectors are used to create large radio telescopes using the principle of superposition. Describing their results in the New Journal of Physics, the team points out that such deviations could affect observations made using arrays, particularly in precision astronomy experiments.
[G Rengaraj et al., New J. Phys. 20 063049 (2018)]

Extracted with permission from an item by Hamish Johnston at physicsworld.com.

NASA launches Parker Solar Probe mission to 'touch' the Sun

NASA has launched a mission to study the Sun's atmosphere and solar wind that will come far closer to our star than any other craft before. The Parker Solar Probe took off today from NASA's Kennedy Space Center in Florida at 03:33 local time aboard a Delta IV rocket. During the mission's seven-year lifespan, it will perform 24 orbits around the Sun coming as close as 6.1 million kilometres to its surface – well within the orbit of Mercury.

The nearest probe to have reached the Sun was the Helios 2 spacecraft, which in 1976 came within 44.5 million kilometres of the Sun's surface. The 635 kg Parker Solar Probe will come near enough to the Sun allowing it to watch the solar wind speed up from subsonic to supersonic and trace how energy and heat move through the corona. This will allow scientists to gain information about what accelerates the solar wind as well as the high-energy particles coming from the Sun, known as solar energetic particles.

To do so, the Parker Solar Probe will carry four instruments. One instrument, dubbed FIELDS and built by the Space Sciences Laboratory at the University

of California, Berkeley, will measure the electric field around the spacecraft with five 2 m-long antennas made of a niobium alloy that can withstand high temperatures. FIELDS will also contain three small magnetometers to measure magnetic fields. The other three instruments are an imager and two dedicated particle analysers.

To withstand the intense temperatures, which can reach almost 1400 C, the spacecraft and instruments will be protected by a 11.4 cm carbon-composite shield. "We'll be going where no spacecraft has dared go before – within the corona of a star," says Parker Solar Probe project scientist Nicky Fox from Johns Hopkins Applied Physics Laboratory. "With each orbit, we'll be seeing new regions of the Sun's atmosphere and learning things about stellar mechanics that we've wanted to explore for decades."
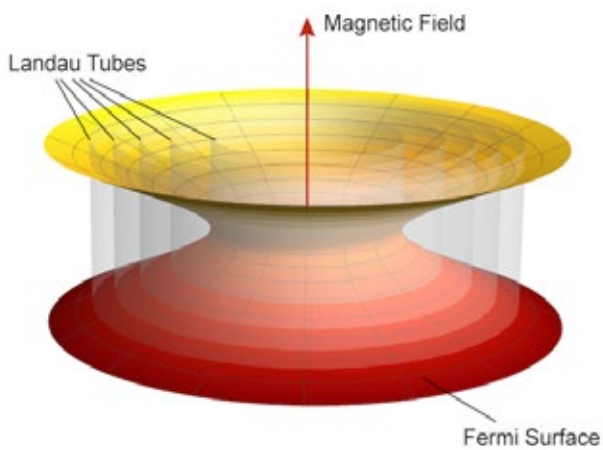
The mission is named after physicist Eugene Parker who was born in 1927 and made several breakthroughs of our understanding of the solar wind and also explained why the Sun's corona is hotter than its surface. Indeed, it is the first NASA mission to be named after a living scientist. Earlier this year the American Physical Society awarded him the Medal for Exceptional Achievement in Research.

Extracted with permission from an item by Michael Banks at physicsworld.com.

Quantum oscillations appear in a Kondo insulator

Researchers have discovered quantum oscillations of electrical resistivity in an insulator for the first time. The new discovery, made in the mixed valence Kondo insulator ytterbium dodecaboride, is unexpected since these oscillations are usually only seen in metals. The result will help shed more light on the electronic properties of these unusual materials, which are important for fundamental studies in condensed-matter physics.

Resistance oscillation reveals the electronic structure of YbB12. (Courtesy: Lu Li)

The orbital motions of conduction electrons on the Fermi surface in metals are quantized in magnetic fields and show up as quantum oscillations in the electrical resistivity of the metal. This so-called Landau quantization is not usually seen in insulators, however. A team of researchers led by Lu Li of the University of Michigan in the US and Yuji Matsuda of the University of Kyoto in Japan has now found an exception in crystals of ytterbium dodecaboride (YbB_{12}). The bulk of this rare-earth intermetallic compound is an insulator but its surface conducts electricity very efficiently. The quantum oscillations observed by Li and Matsuda's teams, surprisingly, come from the insulating bulk.

The researchers obtained their result thanks to measurements using the strongest DC magnetic fields available (of 45 Tesla) at the National High Magnetic Laboratory in Tallahassee, Florida. They passed an electrical current through their sample while applying extremely high magnetic fields and measured the electric voltage decrease in it. This technique, which they performed at different temperatures, allowed them to determine the resistivity of the sample.

"We found that the resistivity of YbB_{12}, which is of a much larger magnitude than the resistivity of metals, exhibits distinct quantum oscillations," explains Li. "These unconventional oscillations arise from the insulating bulk, even though the temperature dependence of the oscillation amplitudes follows the expected and conventional Fermi liquid theory of metals (the "Lifshitz-Kosevich formula").

"This result confirms that Kondo insulators have a dual nature – they are both electrical insulators and itinerant metals," he says. "This duality is a surprising consequence of the strong correlations between the electrons in the material."

The team, which includes researchers from the Université Chretienne Bilingue du Congo, the Japan Synchrotron Radiation Research Institute, the Clarendon Laboratory at the University of Oxford and Ibaraki University, says that it is now repeating its measurements in pulsed magnetic fields. "These studies should help us pin down the angular dependence of the quantum oscillations and allow us the map of the geometry of Fermi surfaces in the insulating state," reveals Li.
[Z. Xiang et al., Science, 30 Aug 2018: eaap9607 DOI: 10.1126/science.aap9607]

Extracted with permission from an item by Belle Dumé at physicswold.com.

Maxwell's demon brings order to an atomic lattice

The famous "Maxwell's demon" thought experiment has been brought to life using lasers to significantly reduce the entropy of a 3D array of ultracold atoms. The work was done by David Weiss and colleagues at Pennsylvania State University who say that such well-ordered arrays of neutral atoms could form the basis of future quantum computers.
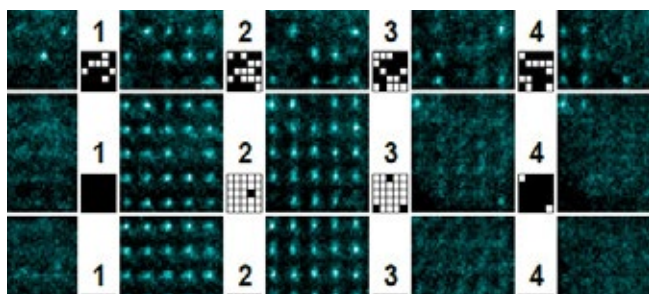
Each row shows the five planes of a 5x5x5 optical lattice. The top row shows the initial random configuration of atoms. The middle and bottom rows show the progression towards having all the atoms in a 5x5x2 sublattice. (Courtesy: Weiss Laboratory/Penn State)

Quantum computing continues to be a hot topic in physics because it could lead to the creation of devices that perform certain calculations exponentially faster than conventional digital systems. Scientists are investigating several technologies to create quantum bits (qubits) and among the front runners are arrays of trapped ions held and also superconducting circuits.

The spin states of neutral atoms held in arrays also hold great promise for making qubits. The fact that such atoms have no charge means that large numbers of them can be trapped very close to one another without mutual interference. One popular kind of trap is the optical lattice, which exploits the interference between pairs of laser beams to set up a standing wave that holds atoms at its nodes or antinodes — depending on whether the force is repulsive or attractive.

The challenge with neutral atoms is being able to engineer interactions between atoms to establish entanglement – one of the basic requirements for quantum computation. This can be done using a controlled NOT gate, which flips the state of one qubit depending on the state of a second qubit. While neutral-atom systems have been used to make two-qubit gates, the error rates of those gates are higher than the trapped-ion or superconducting equivalents.

Weiss and colleagues' work is important because they have minimized the entropy of an atom trap, something that will be important for creating high-fidelity quantum gates. This was done by realizing Maxwell's demon in the lab.

The demon was first proposed in the mid-19th century by James Clerk Maxwell as a challenge to the second law of thermodynamics. The imaginary creature lurks in a pair of gas-filled chambers that is separated by a tiny door. The demon opens the door to allow faster-moving molecules to pass into one of the chambers, and to allow slower moving molecules to pass into the other chamber. Heat is therefore transferred from a colder to a hotter region and the entropy of the system decreases, in apparent violation of the second law.

Rather than sort gas molecules by speed, Weiss and colleagues sorted neutral atoms according to their spatial position. They started by laser cooling a collection of caesium atoms to a few millionths of a degree above absolute zero and then loading them into a 3D optical lattice – made from three pairs of laser beams. Most atoms quickly leave the lattice in such a way that the lattice is left half-full, with each site either empty or occupied by one atom in a random distribution (see figure).

The next step is to convert this half-full lattice of randomly positioned atoms into a smaller sublattice that is completely full and therefore entirely uniform. The team was able to see which of the nodes were occupied, thanks to the light from the cooling lasers scattering off the atoms. They then exploited the fact that the standing-wave nodes can be shifted in space by changing the polarization of one of the laser beams in each pair, as well as the fact that this shift occurs in opposite directions for the two spin states of each atom.

The researchers used an additional pair of tightly focused laser beams plus a source of microwaves to selectively flip the spin of any atom in the lattice while leaving the spins of surrounding atoms undisturbed. A change in the polarization of the relevant lattice laser then allowed them to move that atom relative to the others. Repeating these steps numerous times they were able to convert a half-empty 5x5x5 lattice into a completely full 5x5x2 sublattice. This lowered the lattice entropy by more than a factor of two. [Aishwarya Kumar, et al., Nature 561, 83–87 (2018)] **Extracted with permission from an item by Edwin Cartlidge at physicsworld. com.**

PRODUCT NEWS
Lastek

1. Ocean Optics new LSM Series LED Light Sources available from Lastek.

- UV, Visible, NIR and broadband wavelengths
- Passive cooling design
- Smart controller with color LCD touch screen
- Multiple mounting options (DIN rail, optical bench, rack)
- External trigger option (function generator or trigger signal)

LED light sources are ideal for fluorescence excitation and other measurements requiring narrowband illumination. The innovative optical design of the Ocean Optics LSM LED family provides highly efficient coupling into an optical fiber, ensuring high power for fluorescence excitation where every photon counts.

The LSM LEDs are controlled by the LDC-1 compact single channel driver and controller packed with features and functionality. The LDC-1 controller has an easy to use touchscreen for displaying and accessing key information stored in the LSM LEDs. Proprietary electronics provide stable, high-current operation in continuous, pulsed, and modulation modes. When using the internal modulation mode, the user can select sine, triangle or square waveforms. The LDC-1 also enables LSM LED control using an external source such as a function generator or a trigger/modulation signal from a spectrometer or other electronic device.

2. LaVision introduces two new 4MPx high-speed camera models.

The LaVision Phantom v2640 and Phantom v1840 models are the latest addition to the ultrahigh-speed camera series.

Both camera models have a resolution of 4Mpx and an exceptional image quality as well as a low noise level. The Phantom v1840 achieves up to 4,510 fps at full resolution and the Phantom v2640 up to 6,600 fps. Both camera models feature multiple operating modes (high-speed, correlated double sampling (CDS) and binned) for maximum flexibility. With a minimum interframe time of 500 ns, they are particularly suitable for PIV applications.

LaVision offers both camera models either with a standard F-mount front panel or optionally with an M42 front panel. The cameras are perfectly integrated into LaVision's DaVis 10 software.

3. LASOS He-Ne laser series now available at Lastek.

LASOS helium-neon lasers are available from Lastek in a range of wavelengths and output powers, including modules, power supplies and complete systems.

- Designed for long life, low noise and high stability
- Excellent beam quality
- Standard and customized models
- Single mode or multi mode
- Randomly or linear polarized

Coherent Scientific

Superior Intelligent Spectrograph

The new Kymera 328i imaging spectrograph from Andor Technology is a highly modular spectrograph featuring patented Adaptive Focus, quadruple on-axis grating turret and TruResTM technology delivering superb spectral resolution performance.

The intelligent, motorised Adaptive Focus of the Kymera allows automated access to the best optical performance for any grating, camera or wavelength range configuration. The TruResTM option delivers unmatched spectral resolution for the third-metre focal length spectrograph.

The Kymera 328i sets a new standard when it comes to configurability, being the only imaging spectrograph on the market to offer dual output ports, dual input ports and indexed quadruple grating turret. This provides a unique range of light coupling and spectral performance options to best match current and future setup requirements.

New Large Field of View sCMOS

Andor Technology has released the new Marana ultra-sensitive, deep cooled, back illuminated sCMOS camera. Featuring 95% quantum efficiency and vacuum cooling down to -45oC, Marana represents the ultimate in sCMOS sensitivity and high dynamic range photometry. Marana 4.2B-11 combines a 4.2 megapixel array with 11µm pixels, enabling an impressive 32mm sensor diagonal and offering the largest field-of-view commercially available.

Marana delivers the highest and broadest sCMOS QE profile available peaking at 95%. A UV-enhanced option improves response across the wavelength region between 200nm and 400nm, enveloping both 266nm and 355nm laser lines and presenting a strong solution for applications such as Wafer Inspection and Ultra-cold Ion measurements.

New Precision Current Voltage Source

The MeasureReady 155 precision current and voltage source from Lake Shore Cryotronics combines premium performance with unprecedented simplicity for materials scientists and engineers requiring a precise source of voltage and current.

With extensive experience in low-noise instrumentation for research, Lake Shore has leveraged the latest electronic technologies to reduce in-band and out-of-band noise floors for the MeasureReady 155 source to levels previously only possible using add-on filters. The result is a combination AC/DC current and voltage source that is well-suited to the challenges of characterising sensitive materials and devices, where lower excitation signals are needed and minimum injection of noise into the measurement is required.

For further information please contact Lastek Pty Ltd on 08 8443 8668 or sales@lastek.com.au
sales@coherent.com.au
www.coherent.com.au

Warsash

New VIS and IR high power fibre amplifiers

Azure Light Systems introduces the unique series of high power all fibre laser solutions for greatly improved stability, robustness and unprecedented system integration. The single frequency mode visible and infrared lasers offer unique performance in terms of low noise and high power, combined with the inherent efficiency and stability of fibre lasers.

Standard wavelengths available include 1064, 1030 and 976nm with up to 50W of power in the infrared and 532, 515 and 488nm with up to 10W of power in the visible. Other wavelengths are available on request using an external seed laser, including the customers own seed laser.

Key application areas are:
- Atom trapping
- Atom cooling
- Bose-Einstein Condensates
- Laser pumping
- Holography
- Interferometry
- Spectroscopy

Four channel single photon counting module

Introducing the all new high performance four channel single photon counting modules (SPCM) from Excelitas Technologies. Excelitas Technologies is a global leader focused on delivering innovative, customised optoelectronics solutions.

Excelitas Technologies have extended it's portfolio of low-light-level detection modules with a multi-channel version of the well-known SPCM single photon counting module that is based on a unique silicon avalanche photodiode (SLiK) that has a circular active area of 180μm with a peak photon detection efficiency exceeding 60% at 650nm. Each photodiode is both thermoelectrically cooled and temperature controlled,

ensuring stabilized performance despite changes in the ambient temperature.

The SPCM-AQ4C card uses an improved circuit with a peak count rate >4 M c/s for short bursts of time on all 4 channels and a count rate of 1.5 M c/s for continuous operation. There is a "dead time" of 50 nanoseconds (ns) between pulses. The module requires +2 Volts, +5 Volt, and +30 Volt power supplies. The output of each channel – a TTL pulse that is 4.5 Volts high (into a 50 Ω load) and 25 ns wide – is available at the card edge behind the circuit board. Each TTL pulse corresponds to a detected photon.

F-122 5-axis fibre alignment system

Physik Instrumente, a global leader in the design and manufacture of high precision motion control systems has launched F-122 5-axis fibre alignment system.

The setup of the fibre alignment system consists of three M-122 series motorised linear stages and the WT-85 and WT-100 goniometers. In conjunction with the C-884.6DC controller and C-990.FA1 software it is possible to use the F-122 as a fully automated alignment system for light-transmitting components with the integration of an optical intensity signal. Synchronised operation of the axes is possible which allows for one- or two-dimensional motion paths including spiral paths.

For more information, contact Warsash Scientific on +61 2 9319 0122 or sales@warsash.com.au.

Zurich Instruments

Counter Quantum Analyzer for Parallel Readout of 10 Qubits

The Zurich Instruments UHFQA Quantum Analyzer represents the new standard for multi-qubit readout in ambitious quantum computing projects. The UHFQA measures the state of 10 qubits simultaneously with state-of-the-art speed, fidelity, and innovative signal crosstalk suppression techniques. In dual-sideband operation, a frequency span up to 1.2 GHz is covered. Now, the combination of UHFQA and the HDAWG Arbitrary Waveform Generator forms a complete solution for multi-qubit control and measurement in the baseband.

The UHFQA is used in demanding quantum computing applications with superconducting and spin qubits.

The UHFQA consists of a dual-channel 14-bit arbitrary waveform generator and a dual-channel signal acquisition and analysis unit, both running at a 1.8 GSa/s rate. The analysis unit contains 10 configurable digital filters, each 4 kSamples long, allowing for precise matching to a given qubit transient response. Such a matched filter can significantly improve SNR and readout time compared with unweighted signal integration. Crosstalk suppression by a fully configurable 10 x 10 matrix multiplication allows faithful readout, even as the system size increases. The 32-bit DIO interface enables low-latency transmission of the multi-qubit state for quantum error correction. The UHFQA comes with LabOne software for configuration and measurement. APIs for Python, LabVIEW, MATLAB, and .NET support rapid integration into specialized software environments like QuCoDeS.

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Tel.: +41 44 5150410
info@zhinst.com
http://www.zhinst.com/products

Ice Senses Neutrinos from the Cosmos

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

50 m
Ice Top

IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

1450 m

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

2450 m

86 strings of DOMs, set 125 meters apart

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

60 DOMs on each string

IceCube detector

DeepCore

DOMs are 17 meters apart

Antarctic bedrock

125 m

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