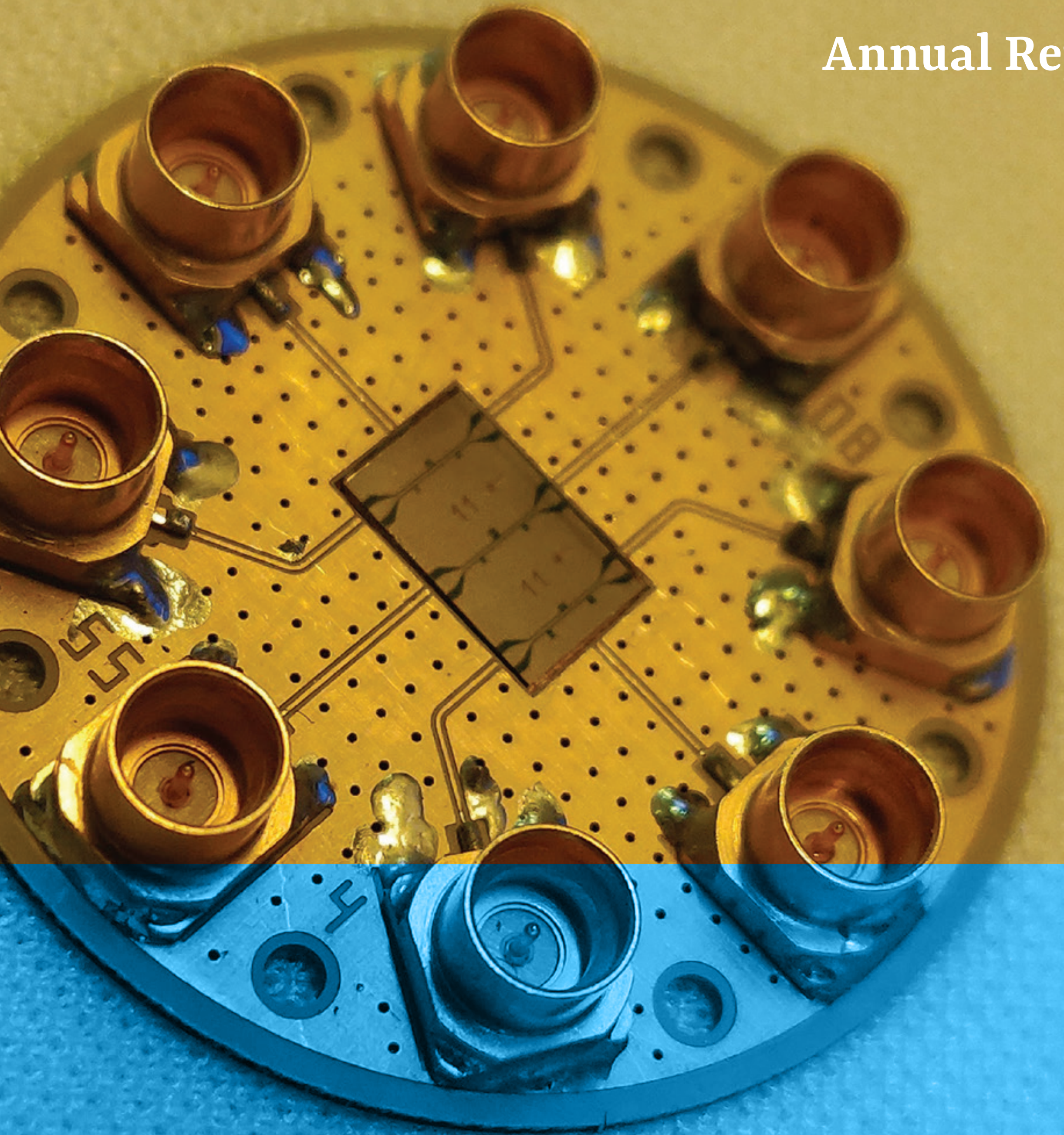
Annual Report 2021



EQUS

Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

EQUS acknowledges the support of the Australian Research Council

Australian Government
Australian Research Council

We also acknowledge the financial and in-kind support provided by our collaborating organisations

The University of Queensland Australia
The University of Sydney
Macquarie University Sydney · Australia
The University of Western Australia
Australian National University

EQUS acknowledges the Traditional Owners of Country throughout Australia and their continuing connection to lands, waters and communities. We pay our respects to Aboriginal and Torres Strait Islander cultures and to Elders past and present. We honour and respect the long tradition of knowledge-making, including in the STEM disciplines of science, technology, engineering and mathematics, of First Nations People.

Cover image
Chip with inductively coupled resonators on printed circuit board, before being mounted in a dilution refrigerator
Image by Amy Navarathna

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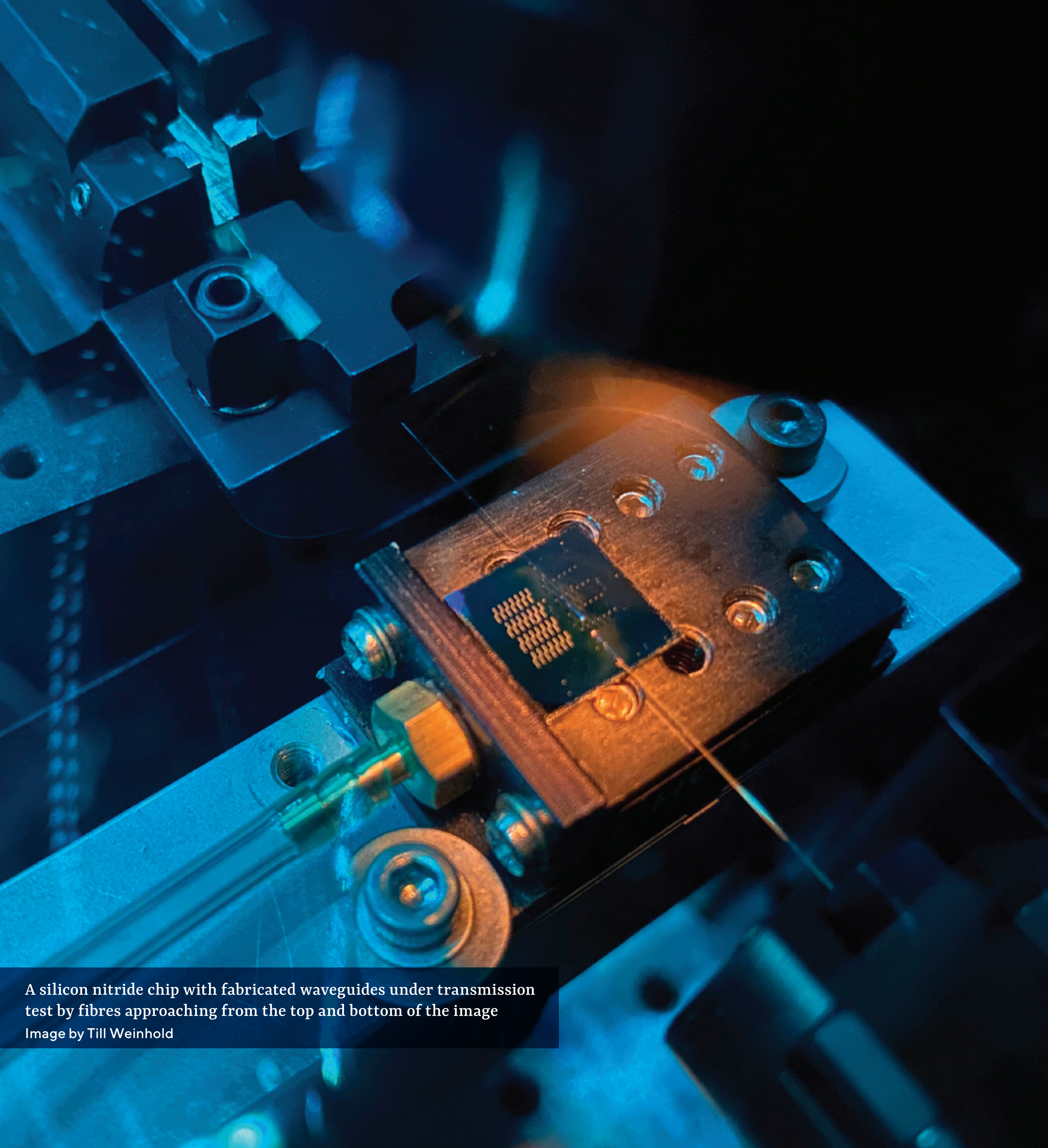


A silicon nitride chip with fabricated waveguides under transmission test by fibres approaching from the top and bottom of the image
Image by Till Weinhold

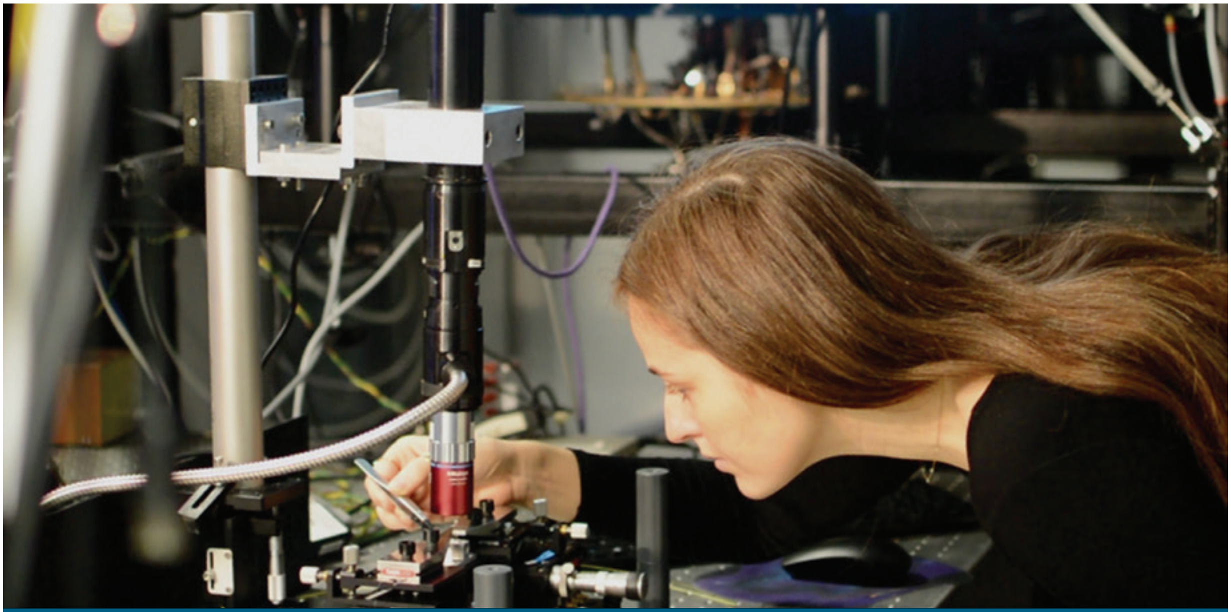
Executive summary

Quantum technologies use the properties of quantum mechanics for practical applications. They are found in our everyday lives, for example, in smart phones and cars, and in industrial applications in manufacturing, engineering and imaging.

Today's technology captures only a small fraction of the potential of quantum physics. New developments in research and engineering mean a new generation of technologies. These technologies have potential in fields such as health, telecommunications and finance, and will benefit business and society.

The Australian Research Council Centre of Excellence for Engineered Quantum Systems (EQUS) is a seven-year investment of more than $40 million by the Australian government in quantum technologies. EQUS is solving the most challenging research problems at the interface of basic quantum physics and engineering, working with partners in industry to translate discoveries into practical applications and devices, and training a new generation of scientists in cutting-edge research, innovation and entrepreneurialism.

This annual report covers EQUS activities for the 2021 calendar year. It forms part of our official reporting and accounting requirements to the Australian Research Council. Centre activities encompass research, research translation, equity, diversity and inclusion, mentoring and career development, outreach and education, operations and finance.



EQUS researcher Yasmine Sfendla moving her silicon chip around on a testing stage, hoping to find a sign of trapped photons
Image by Yasmine Sfendla and Erick Romero

Director’s update

Well it turns out that 2021 was, to quote Yogi Berra, déjà vu all over again. Our hopes for a swift return to the old normal were dashed, but on the positive side we now have knowledge, information, vaccines, protocols and legislation, all of which are enabling us to reclaim some of what we have missed. What is clear is the significant role that research has had in the COVID-19 global crisis — more specifically, what may be achieved through a large, concerted research effort, where talented researchers are focused towards a common goal and supported through major investment, collaborative multidisciplinary approaches and world-class infrastructure. EQUS is representative of such an endeavour, albeit on a smaller scale, as we work towards our vision to exploit the potential of quantum science and develop a range of transformational technologies that will benefit society.

Our resolve that quantum technology is the key to many of the grand challenges that will transform the world was reinforced in 2021 by a few important government announcements. First was the announcement of trilateral collaboration between Australia, the United Kingdom and the United States to enhance our joint capabilities and interoperability on cyber capabilities, artificial intelligence and quantum technologies. Two months later, the Federal Government confirmed its commitment to quantum technology through a $111 million investment designed to secure Australia’s quantum future, of which $70 million will be used to establish a Quantum Commercialisation Hub. This news was quickly followed by the announcement that Australia and the United States had signed a joint statement to cooperate on quantum technology innovation and commercialisation. In New South Wales, the State Government announced investment in the creation of a quantum technology centre for the New South Wales transport network. This was all welcome news for EQUS, and especially for our students and early-career researchers, who will be perfectly placed to join the burgeoning quantum technology industry in Australia once the Centre concludes.

2021 was also the year of the EQUS ARC midterm review. An important process for all Centres of Excellence and undertaken in the fourth year of operation, our performance was evaluated against the scheme’s objectives and agreed performance targets. The review offered us an opportunity to reflect on our progress and achievements, and through the feedback gained from the review develop a plan that will allow us to build on our strengths for our remaining three years of operation. The process was comprehensive but extremely successful and I thank all our members, research partners, stakeholders and research office teams who supported us through their involvement with the submission, preparation activities, interviews and/or the response to the recommendations. A special thanks to our operations team who were integral to each part of the year-long activity and of course to the ARC review panel who provided such thoughtful and thought-provoking feedback and insights.

Despite the continued disruptions and restrictions enforced variously by governments and/or universities that limited travel and events, we were pleased to be able to hold several Centre events: the Coogee Quantum Theory Workshop, Python Workshop, Idea Factory and Annual Workshop. We relaunched our fortnightly seminar series and in two rare travel windows I even snuck in visits to our teams at Macquarie University and the Australian National University.

On the research front, the Centre continues to flourish despite significantly reduced lab access for many of our members. In the pages ahead, you will get to see a few of the highlights of what has been another exciting year of scientific discovery and engineering of quantum machines. Despite the domestic and international travel restrictions, our members still participated in national and international conferences via virtual attendance or presentations (I can personally attest to getting all the jetlag with none of the travel!). And many of our talented researchers were recognised through prestigious awards, including:

- Professor Halina Rubinsztein-Dunlop was awarded the 2021 C.E.K. Mees Medal by the Optical Society of America
- Professor Warwick Bowen received the 2020 John Love Award from the Australian and New Zealand Optical Society
- Dr Magdalena Zych was awarded the 2020 Ruby Payne Scott Award by the Australian Institute of Physics
- Dr Fabio Costa was awarded a Queensland 2021 Young Tall Poppy Science Award by the Australian Institute for Policy and Science
- Dr Sascha Schediwy won Academic of the Year and the overall Excellence prize in the 2021 Australian Space Awards
- Catriona Thomson was awarded the 2021 EFTF–IFCS Best Student Paper Award

Finally, I'd like to extend a sincere thank you to all our members for their continuing contributions through what was another challenging year, and to our Executive Committee, Advisory Committee and Scientific Advisory Committee for their ongoing drive, support and advice. I look forward to working with all of you in 2022 and seeing what we next unfurl on the world!

Professor Andrew White
Centre Director

Governance

ADVISORY COMMITTEE

The Advisory Committee contributes to the Centre's strategic direction and supports links between academia, industry and government. The committee met virtually in May and December 2021.

The Advisory Committee consists of:

Professor Christine Williams

- **Professor Christine Williams (Chair),** Chair at Life Sciences Queensland, Chair of the Women in Economics Network in Queensland, Activator at SheEO, Adjunct Professor at The University of Queensland
- **Dr David Bird,** Science, Technology and Research (STaR) Shot Leader, Defence Science and Technology Group
- **Dr Gregory Clark AC FAA FTSE,** Chair at KaComm Communications
- **Dr Bronwyn Evans HonFIEAust FTSE CPEng,** Director at GME, CEO at Engineers Australia, VP (Finance) at ISO
- **Dr Ben Greene,** CEO at Electro Optic Systems
- **Professor Jim Williams AM FAA FTSE,** Emeritus Professor, Department of Electronic Materials Engineering, Australian National University

SCIENTIFIC ADVISORY COMMITTEE

The Scientific Advisory Committee provides independent scientific expertise and advice regarding the Centre's research program. The committee met virtually as part of the EQUS Annual Workshop in December 2021.

The Scientific Advisory Committee consists of:

Professor Sir Peter Knight

- **Professor Sir Peter Knight FRS (Chair),** Emeritus Professor at Imperial College London, principal of the Kavli Royal Society International Centre, former president of the Institute of Physics and the Optical Society of America
- **Professor Alain Aspect ForMemRS,** Laboratoire Charles Fabry, Institut d'Optique
- **Professor Rainer Blatt ForMemNAS,** Institute of Experimental Physics, Universität Innsbruck
- **Professor John Clarke FRS,** Department of Physics, University of California, Berkeley
- **Professor Birgitta Whaley FAPS,** Whaley Research Group, University of California, Berkeley

CENTRE EXECUTIVE AND DIRECTORATE

The Centre Executive includes the Centre Director, Deputy Directors, Chief Operating Officer, Node Directors and Translational Research Program Director. The Executive meets monthly and is responsible for the development and execution of the Centre's strategic direction. The Executive also provides leadership and direction to the Centre's operations, ensuring the Centre is managed responsibly and successfully.

The Executive consists of:

- **Professor Andrew White FAA (Chair),** Director
- **Dr Sally Shrapnel,** Deputy Director
- **Associate Professor Thomas Volz,** Deputy Director, Node Director (MQ)
- **Katrina Tune,** Chief Operating Officer
- **Dr John Bartholomew,** Node Director (USYD)
- **Associate Professor Kirk McKenzie,** Node Director (ANU)
- **Professor Michael Tobar FAA,** Node Director (UWA)
- **Professor Halina Rubinsztein-Dunlop AO FAA,** Translational Research Program Director

The Centre Directorate, which comprises the Centre Director, Deputy Directors and Chief Operating Officer, meets weekly to discuss priority operational issues that may be progressed without Executive approval.

2021 saw substantial changes to EQUS' leadership team. In January, EQUS welcomed Katrina Tune as the new Chief Operating Officer, taking over from Lisa Walker. John Bartholomew and Kirk McKenzie joined the Centre Executive as the new Node Directors of USYD and ANU, taking over from Stephen Bartlett and Daniel Shaddock, respectively.

In July, the Centre welcomed two new Deputy Directors, Sally Shrapnel and Thomas Volz, who have jointly taken over the role from Tom Stace.


Andrew White


Sally Shrapnel

Sally Shrapnel has been a theorist with EQUS since it commenced in 2018, bringing her research on quantum foundations, causality and machine learning. Combining her experience as a medical doctor with her machine learning research, she also leads an international project across 50 countries to predict acute kidney injury in patients with COVID-19.

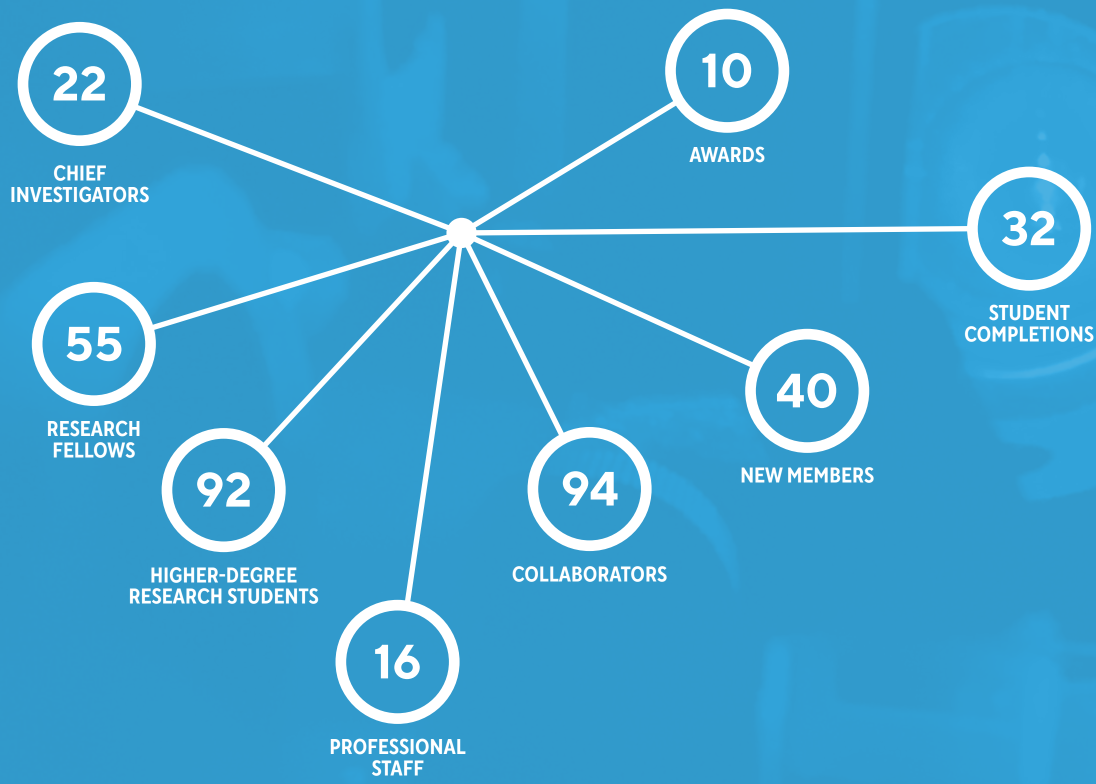

Thomas Volz

Thomas Volz has been with EQUS as an experimentalist since its commencement in 2018 and was a member of the previous iteration of the Centre from 2013 to 2017. He has worked with several different quantum systems, including ultracold quantum gases, integrated quantum photonic devices and nanodiamonds, making substantial contributions to each field.


Katrina Tune

Katrina Tune joined EQUS from the ARC Centre of Excellence for Robotic Vision, where she was also Chief Operating Officer. She has more than 15 years' experience working in Australian universities. She is also a Director on the Board of Epilepsy Queensland, a cause close to her heart. Katrina is passionate about transformational leadership, organisational culture, and equity, diversity and inclusion.

Our people: Overview



EQUS, led by Laureate Professor Andrew White, is a collaborative research endeavour, comprising researchers from five leading Australian universities, 16 Partner Organisations across Australia, North America, the United Kingdom and Europe, and various other national and international organisations.

Our strength, without a doubt, lies in our people: talented researchers who are passionate about using quantum physics to develop technologies that will benefit society, professional staff that support and enable our research success, and an Advisory Committee and Scientific Advisory Committee who help guide and shape our strategic direction.

Our people: Awards and recognition

In 2021, several EQUS members were recognised for their contributions to quantum science and technology.

Andrew White was awarded a 2021 Australian Laureate Fellowship, to create energy-efficient artificial intelligence platforms using quantum technologies. He will take up the Laureate in 2022.

Michael Tobar was named the Distinguished Lecturer for Frequency Control for 2021–22 by the IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society. He will deliver 20–40 lectures at institutions around the world during his term (July 2021 to December 2022).

Warwick Bowen received the 2020 John Love Award from the Australian and New Zealand Optical Society for his innovations and technical advances in the field of optics and photonics.

Magdalena Zych was awarded the 2020 Ruby Payne-Scott Award by the Australian Institute of Physics for her development of an innovative new framework that incorporates relativistic time dilation into the theory of quantum mechanics, discovery that time dilation leads to a novel form of quantum entanglement and decoherence, and subsequent proposal of the new paradigm of 'quantum clock interferometry'. She was also awarded a 2021 ARC Future Fellowship for a study on gravity effects in quantum clocks and sensors.

EQUS start-up **Redback Systems** received the 2021 John Love Award from the Australian and New Zealand Optical Society for the translation of optical research out of the laboratory to a commercial product—the RS40K Echelle Spectrometer.

Fabio Costa was awarded a Queensland 2021 Young Tall Poppy Science Award by the Australian Institute for Policy and Science, in recognition of his efforts to improve science literacy. As part of the award, he will participate in activities to promote science among school students, teachers and the broader community.

David Gozzard was awarded an ABC Top 5 Science media residency, providing him the opportunity to undertake a two-week online residency with ABC Radio National to learn the craft of communicating with a wide audience from some of Australia's best broadcasters and how to develop content across radio and digital platforms. He was also named third place in the 2021 Rising Stars of UWA Science.

Sascha Schediwy won Academic of the Year and the overall Excellence prize in the 2021 Australian Space Awards for his outstanding achievements in space research, in particular the use of free-space laser links to send communication and timing signals through Earth's turbulent atmosphere and eventually to outer space.

Catriona Thomson was awarded the 2021 EFTF–IFCS (Joint Conference of European Frequency and Time Forum and the IEEE International Frequency Control Symposium) Best Student Paper Award for her paper *Using precision frequency metrology for dark matter searches*.

Eugene Sachkou attended the 70th Lindau Nobel Laureate Meeting, deferred from 2020 because of COVID-19, after being awarded the opportunity in 2020.

Ben McAllister was named first place in the 2021 Rising Stars of UWA Science.

Halina Rubinsztein-Dunlop was awarded the 2021 C. E. K. Mees Medal by the Optical Society of America for the discovery and development of an 'optical wrench'. She was also named SPIE's June Luminary for her contribution to optical trapping and was awarded the 2020 Harrie Massie Medal by the Australian Institute of Physics for her pioneering work in laser micromanipulation, atom and quantum optics, ultracold atomic gases, nano-optics and biophotonics.

The C. E. K. Mees medal recognises Halina's pioneering innovations in the transfer of optical angular momentum to particles, using sculpted light for laser manipulation on atomic-, nano- and microscales to generate fundamental insight and provide powerful probes to biomedicine.

Her work in the field of optical micromanipulation began in the 1990s and initiated a quiet revolution that enabled numerous developments in the field and paved the way for efficient, entirely optically driven micromachines. She was the first to demonstrate the transfer of angular momentum from light to microscopic objects within the light field, causing the objects to rotate. She pioneered a method for producing micrometre-sized birefringent spheres (which bend light in two different ways) and was the first to demonstrate an optical system that could accurately measure the torque exerted by a trapping beam on a rotating birefringent sphere. These discoveries have facilitated the study of a wide range of phenomena, including cell adhesion, rheology of microfluids, DNA twisting, microscopic forces and the development of synaptic connections, exemplifying the idea that 'optics transcends all boundaries'.


Halina Rubinsztein-Dunlop

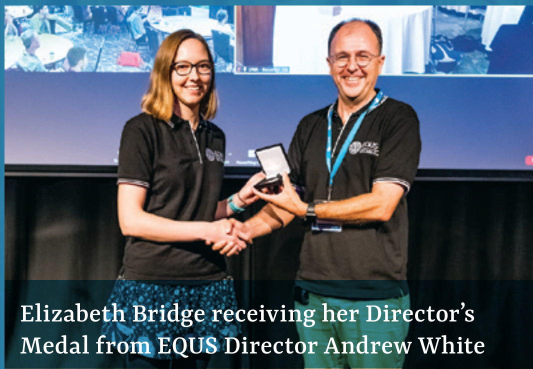
Halina also has a distinguished record of achievement in laser cooling and trapping of atoms, and her group have demonstrated experimental milestones in quantum chaos and dynamic tunnelling of ultracold atoms. Recently, they successfully observed Onsager vortex clusters, a fundamental coherent structure in two-dimensional turbulence, an observation that had evaded experimental attempts since the prediction of these structures more than 70 years ago.

She is the first woman to receive the C. E. K. Mees Medal in its 60-year history.

Our people: EQUS awards

DIRECTOR'S MEDAL

Elizabeth Bridge



Elizabeth Bridge receiving her Director's Medal from EQUS Director Andrew White

The Director's Medal is presented to a researcher who not only exhibits the spirit of collaborative enquiry required to advance research in quantum physics but also goes above and beyond to assist with service activities within the Centre.

Elizabeth Bridge is a Research Fellow in the Quantum Optics Laboratory at UQ, developing quantum optomechanical sensors that function at room temperature and the technology to translate these sensors into applications. She is an active participant in all aspects of the Centre and regularly demonstrates a willingness to stand up for EQUS' values. She has become an unofficial mentor to PhD students in her group, is a member of two Centre committees, and has initiated or participated in numerous outreach and training activities for EQUS members, the broader physics community and the general public.

CENTRE CITIZEN

Catriona Thomson

Catriona Thomson receiving her Centre Citizen award from UWA Node Director Michael Tobar

The Centre Citizen award is presented to the EQUS member who best represents the aspirations of the Centre through their passion and commitment to the Centre's culture.

Catriona Thomson is a PhD student in the Quantum Technologies and Dark Matter Laboratory at UWA, working on dark-matter detection using precision frequency metrology. An active member of EQUS, she participated in the Centre's midterm review as a member of the student representative panel. She was involved in two key public engagement activities in 2021, the Clear as Quantum podcast and the WA Quantum and Dark Matter Road Trip. She has already established an international collaboration with Massachusetts Institute of Technology, is involved in cross-node collaborations and won the 2021 EFTF-IFCS Best Student Paper Award.

BEST TEAM PROJECT

Michael Biercuk, Ivan Kassal, Cornelius Hempel, Ryan MacDonell and **Claire Edmunds** for their work on analogue quantum simulation of chemical dynamics

BEST COLLABORATIVE PAPER

Tom Stace, David Tuckett and **Terry Farrelly** for their paper exploring the development of tensor-network codes

BEST PROFILE-RAISING ACTIVITY

Quantum and Dark Matter Road Trip team: **Michael Tobar, Ben McAllister, Cindy Zhao, Jeremy Bourhill, Aaron Quiskamp, Catriona Thomson, Elrina Hartman, William Campbell** and **Linda Barbour**

Clear as Quantum podcast team: **Lachlan Rogers, Elizabeth Bridge, Yasmine Sfendla** and **Catriona Thomson**

BEST CONTRIBUTION TO PUBLIC DEBATE

Ben Brown and **Pablo Bonilla** for their leadership on quantum physics in the public arena in relation to their work on error-correcting codes

THREE-MINUTE THESIS COMPETITION

First place: **Amy Navarathna**

Second place: **Cindy Zhao**

Third place: **David Gozzard**

POSTER COMPETITION

First place: **Markus Rambach** and **William Campbell**

Second place: **Carolyn Wood** and **Zhonghua Ma**

Third place: **Rohit Navarathna** and **Dat Thanh Le**

PITCH COMPETITION

First place: **Lauren McQueen**

Second place: **Christina Giarmatzi**

Third place: **Eric He**

EQUS award recipients at the EQUS Annual Workshop in Noosa: (standing, left to right) Rohit Navarathna, Carolyn Wood, Amy Navarathna, Yasmine Sfendla, Markus Rambach, Christina Giarmatzi; (seated, left to right) Tom Stace, Lauren McQueen, Elizabeth Bridge, Dat Thanh Le, Eric He, Zhonghua Ma

Our people: Team

CHIEF INVESTIGATORS

Andrew White *UQ*
Sally Shrapnel *UQ*
Thomas Volz *MQ*
Andrew Doherty *USYD*
Arkady Fedorov *UQ*
Arne Grimsmo *USYD*
Daniel Burgarth *MQ*
David Reilly *USYD*
Gavin Brennen *MQ*
Gerard Milburn *UQ*
Halina Rubinsztein-Dunlop *UQ*
Jacqui Romero *UQ*
John Bartholomew *USYD*
Kirk McKenzie *ANU*
Magdalena Zych *UQ*
Matthew Davis *UQ*
Maxim Goryachev *UWA*
Michael Biercuk *USYD*
Michael Tobar *UWA*
Stephen Bartlett *USYD*
Tom Stace *UQ*
Warwick Bowen *UQ*

PARTNER INVESTIGATORS

Alessandro Fedrizzi *Herriot-Watt University*
Alexia Auffèves *Institut Néel*
Andreas Wallraff *ETH Zurich*
Fedor Jelezko *Ulm University*
Holger Müller *UC Berkeley*
Ian Walmsley *University of Oxford*
Jörg Schmiedmayer *TU Wien*
Lorenza Viola *Dartmouth College*
Mark Baker *UQ*
Markus Aspelmeyer *University of Vienna*
Michael Wouters *NMI*
Oriol Romero-Isart *IQOQI*
Pascale Senellart-Mardon *CNRS*
Peter Zoller *IQOQI*
Peter Wolf *CNRS*
Robyn Starr *MOG Laboratories*
Wolfram Pernice *Universität Münster*

Some of our Chief Investigators at the EQUS Annual Workshop in Noosa: (left to right) Andrew White, Magdalena Zych, Jacqui Romero, Halina Rubinsztein-Dunlop, Matthew Davis, Arkady Fedorov, Tom Stace and Warwick Bowen

ASSOCIATE INVESTIGATORS

Alán Aspuru-Guzik *University of Toronto*
Alan Robertson *USYD*
Alexei Gilchrist *MQ*
Andrew Sutton *ANU*
Behnam Tonekaboni *Griffith University*
Ben Baragiola *RMIT University*
Ben McAllister *UWA*
Chris Ferrie *UTS*
Christina Giarmatzi *UTS*
Clemens Müller *Zurich Instruments*
Cornelius Hempel *Paul Scherrer Institute*
Cyril Laplane *MQ*
Daniel Shaddock *ANU*
David Gozzard *UWA*
Eugene Ivanov *UWA*
Felix Miranda *NASA Glenn Research Centre*
Ian Manchester *USYD*
Ivan Kassal *USYD*
Jacinda Ginges *UQ*
Jennifer Ogilvie *University of Michigan*
Jingbo Wang *UWA*
Joan Leach *ANU*
Jonathan Home *ETH Zurich*
Joshua Combes *UQ*
Kae Nemoto *National Institute of Informatics*
Kavan Modi *Monash University*
Lachlan Rogers *University of Newcastle*
Lawrence Lee *UNSW*
Lute Maleki *OEwaves*
Marco Tomamichel *National University of Singapore*
Martin Ringbauer *Universität Innsbruck*
Matthew Woolley *UNSW*
Maxime Richard *CNRS*
Michael Hush *Q-CTRL*
Michael Vanner *Imperial College London*
Mikolaj Schmidt *MQ*
Nathan Langford *UTS*
Nicholas King *USYD*
Peter Lodahl *University of Copenhagen*
Peter Jacobson *UQ*
Peter Rohde *UTS*
Robert Casson *University of Adelaide*
Sahand Mahmoodian *USYD*
Salah Sukkarieh *USYD*
Sascha Schediwy *UWA*
Sujatha Raman *ANU*
Susan Coppersmith *UNSW*
Terence Rudolph *Imperial College London*
Tyler Neely *UQ*
Victor Flambaum *UNSW*
Vladimir Kruglov *UQ*
William Munro *NTT Basic Research Laboratories*
Yuval Sanders *MQ*
Zixin Huang *MQ*

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Angela Karanjai *USYD*
Ben Brown *USYD*
Byron Villis *USYD*
Christopher Baker *UQ*
David Tuckett *USYD*
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Moying Lyu *UWA*
Robert Limina *UWA*
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Fatemeh Mohit *UQ*
Germain Tobar *UQ*
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Jacinta Rahebmol May *USYD*
Joseph Pham *USYD*
Juan Pablo Bonilla Ataides *USYD*
Justin Brown *USYD*
Michael Robinson *USYD*
Michael Ma *USYD*
Sophia Kurianski *USYD*
Xanda Kolesnikow *USYD*

COMPLETIONS

PhD

Akram Youssry *UTS*
Characterization and control of quantum systems using machine learning and information theory

Benjamin Dix-Matthews *UWA*
Coherent optical transmission through atmospheric turbulence

Catxere Casacio *UQ*
Quantum-enhanced microscopy

Claire Edmunds *USYD*
Error characterisation and reduction in trapped ion quantum computers: one woman's guide to the ion-ing

Guillaume Gauthier *UQ*
Transport and turbulence in quasi-uniform and versatile Bose-Einstein condensates

Kaumudibikash Goswami *UQ*
Applications of higher-order maps

Michael Kewming *UQ*
High-dimensional quantum information

Parth Girdhar *USYD*
Probing foundations of quantum mechanics: a study into nonlocality and quantum gravity

Paul Sibley *ANU*
Scaling optical phased arrays

Paul Webster *USYD*
Fault-tolerant logical operators in quantum error-correcting codes

Prahlad Warszawski *USYD*
Quantum trajectories for, and as, understanding

Robert Harris *UQ*
Fault tolerance and error benchmarking for quantum technologies

Stefan Forstner *UQ*
Probing quantum macroscopicity with cavity optomechanics

Thomas Bell *UQ*
Engineering time-averaged optical potentials for Bose–Einstein condensates

Thomas Smith *USYD*
Entanglement and measurement of solid-state qubits

Master's

Jay Mummery *UWA*
Optomechanical systems influenced by the thermal Casimir force

Lyra Cronin *MQ*
Applications of novel NV maser technology

Sebastian Malewicz *UQ*
Implementation of adaptive optics to maximize single-photon collection efficiency

Honours

Anthony O'Rourke *USYD*
Solving for the spectrum of the GKP quantum error correcting code using the Zak basis

Cassandra Bowie *UQ*
Applying quantum machine learning to classify classical data

Fatemeh Mohit *UQ*
Towards better quantum light with machine learning

Germain Tobar *UQ*
Tests of spontaneous wavefunction collapse with qubit-coupled mechanical resonators

Haoyuan (Jacky) Luo *USYD*
Critical system with the multi-scale entanglement renormalisation ansatz and wavelets

James Lavis *UQ*
Detecting non-equilibrium quasiparticle bursts in granular aluminium resonators

Joseph Pham *USYD*
Towards electromagnetically induced transparency cooling of large 2D-ion crystals in a Penning trap

Juan Pablo Bonilla Ataides *USYD*
Universal fault-tolerant quantum computation in a bilinear array of SiMOS quantum dots

Lauren McQueen *UQ*
Tunnelling of a quantum vortex in a BEC superfluid

Michael Robinson *USYD*
A high-data-rate time-correlated single-photon counter for site-resolved imaging of large trapped-ion crystals

Simeon Simjanovski *UQ*
Flow instabilities at a superfluid boundary

Sophia Kurianski *USYD*
A hybrid entangled photon-pair source to connect superconducting quantum computers

Xanda Kolesnikow *USYD*
Realising the GKP code using periodic driving

Zachary Kerr *UQ*
Magnetic field cancellation for spinor Bose–Einstein condensates

Our people: Life after EQUS

DAVID TUCKETT

David Tuckett joined EQUS as a PhD student at USYD, working with Chief Investigator Stephen Bartlett and former Chief Investigator Steven Flammia. In 2018, he received the EQUS prize for Best Student Paper for his work *Ultrahigh error threshold for surface codes with biased noise* (*Phys. Rev. Lett.* 120:050505).

After completing his PhD (*Tailoring surface codes: improvements in quantum error correction with biased noise*), David became a Research Fellow, continuing his work on quantum error correction and fault-tolerant quantum computing. As part of this, he developed QECSIM, an open-source Python software package for simulating quantum error correction, which was released publicly in February 2021.

Alongside his research, David was a member of EQUS' Quantum for Educators committee, helping to develop quantum-related resources and training for Australian science teachers.

He served as the EQUS Research Fellow Node Representative for USYD and participated in the Centre's midterm review. In November 2021, he left EQUS to take up an industry position at PsiQuantum.

"At PsiQuantum, I work with a highly talented and motivated team dedicated to building the world's first useful quantum computer. In particular, we are targeting a fault-tolerant error-corrected machine based on silicon photonic technology. My role involves exploring novel fault-tolerant schemes and evaluating their performance through the development of full-stack simulations. An aspect of this work that I particularly enjoy is the requirement to dive deep into innovations to ensure their practical relevance."

"I find my involvement within EQUS as a student and research fellow at the University of Sydney to be invaluable. The experience gained and connections made through collaborations, committees, workshops, mentoring and the EQUS midterm review have all helped with the transition to a career in industry. More specifically, the support of the EQUS Translational Research Laboratory in developing open-source research software was particularly relevant in preparing and showcasing my skills for my current role."

Adil Gangat

Physics & Informatics (PHI) Laboratories

After completing a postdoctoral fellowship at UQ, Adil Gangat moved to California, where he works as a Senior Research Scientist at Physics & Informatics (PHI) Laboratories, part of NTT Research.

Catxere Casacio

University of Surrey

After completing her PhD at UQ, Catxere Casacio moved to the UK to take up a postdoctoral research fellowship in experimental quantum biology in the Quantum Biophotonics Group at the University of Surrey.

Claire Edmunds

Universität Innsbruck

After completing her PhD at USYD, Claire Edmunds was awarded an ESQ fellowship from the Austrian Academy of Science, allowing her to take up a postdoctoral fellowship at Universität Innsbruck.

Germain Tobar

University of Cambridge

After completing Honours at UQ, Germain Tobar moved to the UK to undertake a Master of Advanced Studies in Mathematics at the University of Cambridge.

Michael Kewming

Trinity College Dublin

After completing his PhD and a postdoctoral fellowship at UQ, Michael Kewming moved to Ireland to take up a postdoctoral fellowship at Trinity College Dublin.

Prahlad Warszawski

Port Hacking High School

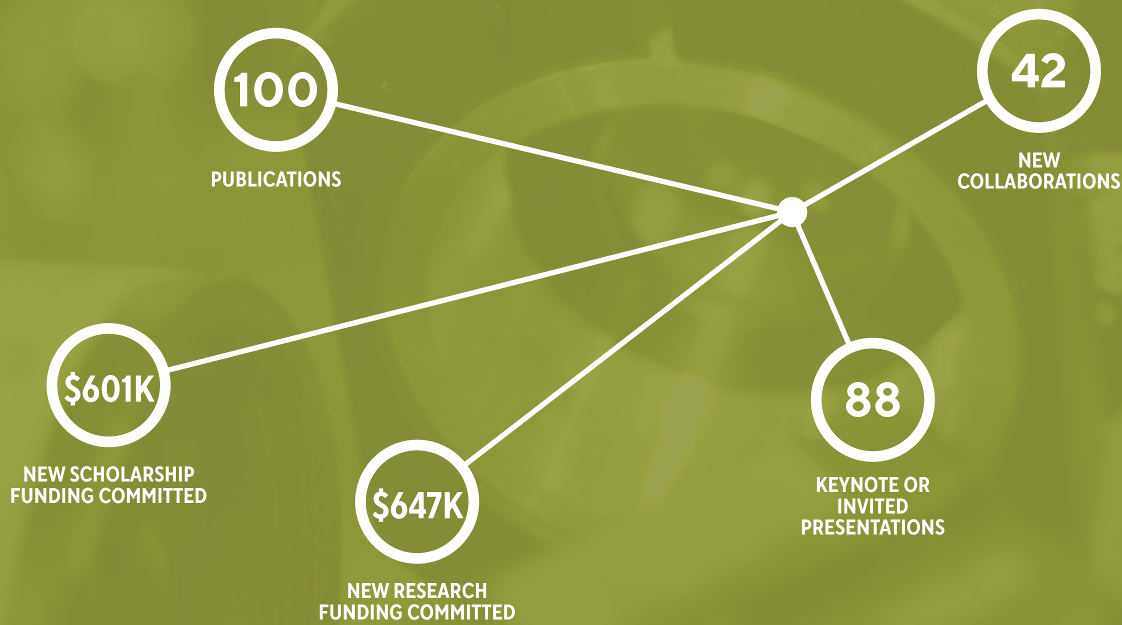
After completing his PhD at USYD, Prahlad Warszawski did a Master of Secondary Teaching and now teaches mathematics at Port Hacking High School in Sydney.

Our research: Overview

EQUS' mission is to engineer the quantum future by building quantum machines that harness the quantum world for practical applications. We are solving the most challenging research problems at the interface of basic quantum physics and engineering.

Our research encompasses theory and experiment, and is organised around the following research programs:

1. **Designer quantum materials**
2. **Quantum-enabled diagnostics and imaging**
3. **Quantum engines and instruments**
4. **1kQubit flagship**
5. **Quantum clock flagship**



Designer quantum materials

Harnessing quantum many-body physics and exquisite control of individual quantum systems to create quantum materials from which quantum machines can be built

Quantum-enabled diagnostics and imaging

Developing prototypes of the sensing and imaging components required for a quantum machine to interact with its environment

Quantum engines and instruments

Understanding quantum engines and instruments so that quantum machines with tens or hundreds of individual components may be designed and manipulated

1kQubit flagship

Developing the theoretical foundations for a useful fault-tolerant quantum processor

Quantum clock flagship

Developing the hardware, architecture and theoretical foundations for improved clock technologies

Designer quantum materials

The Designer Quantum Materials program aims to realise new phases of quantum matter by scaling up today's isolated quantum components and engineering highly entangled, strongly interacting quantum systems, with individual control and measurement of each component.

2021 HIGHLIGHTS

In 2021, EQUS researchers made substantial progress in this program across a wide range of topics, including quantum chemistry, quantum information and networks, light–matter interaction and control, superconducting qubits and quantum cellular automata.

Key advances are as follows:

Experimental platforms

- Analogue quantum simulation of quantum chemical dynamics in a trapped-ion system
- Cryogenic CMOS chip that enables in-fridge control of quantum systems
- Robust and efficient quantum-state tomography of qudits encoded in the shape of light (see page 26)

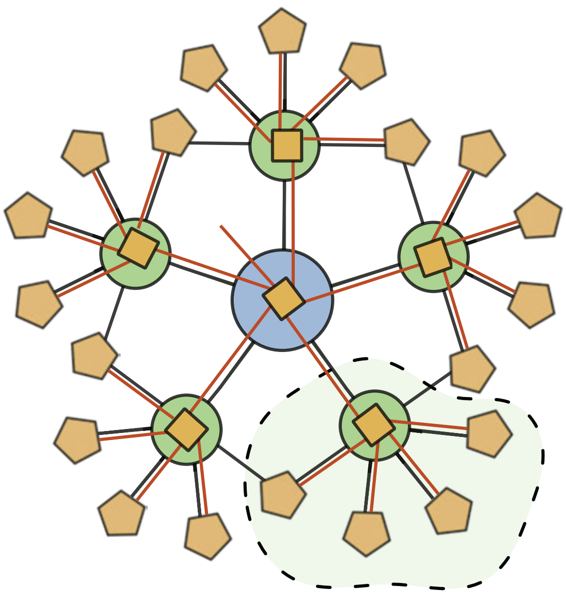
Theoretical advances

- Identification of quantum cellular automata dynamics that efficiently solves the density classification problem
- Numerical toolkit for analysing hybrid superconducting–semiconducting electronic devices
- Tensor-network codes for quantum error correction (see page 25)

TENSOR-NETWORK CODES[1,2]

EQUS researchers have developed generalised quantum error-correcting codes that enable new codes to be generated with no additional work, and an efficient way of testing the quality of the new codes.

Quantum computers offer exciting speed-ups compared to current classical computers in solving some important problems. To ensure that quantum computers function correctly, good quantum error-correcting codes are vital. One way to judge the quality of an error-correcting code is to calculate its distance (the higher the distance, the better the code), but doing so is very challenging.



Example holographic code composed of five-qubit code tensors after boundary contraction
Image by Terry Farrelly

The EQUS team found a new way to represent and build quantum error-correcting codes, by 'gluing together' smaller codes. They also found an efficient way to calculate the distance of the new codes, which allows them to quickly check how good any new codes are.

The preprint on local tensor-network codes won EQUS' Best Collaborative Paper for 2021.

DEFINITIONS

Quantum error correction is an essential aspect of a useful quantum computer, providing a way of protecting quantum information from being lost or corrupted by, for example, interactions with the environment.

The new codes, called tensor-network codes, enable the generalised construction of all known stabiliser (or holographic) codes. The general feature of these codes is that an almost arbitrary graph can be used to generate a large family of codes, enabling the generation of new codes with no additional work. The codes also come with a standard decoder that uses tensor-network contraction to decode arbitrary new codes. It is the first efficient decoder for holographic codes against Pauli noise and a rare example of a decoder that is both efficient and exact.

To simulate these quantum error-correcting codes and understand their properties, the researchers wrote a package in the Julia programming language. The next step is to release the code publicly on GitHub, so that others can try gluing together their own error-correcting codes.

1 T Farrelly, RJ Harris, NA McMahon & TM Stace. **Tensor-network codes.** *Phys. Rev. Lett.* 127:040507 (2021)

2 T Farrelly, DK Tuckett & TM Stace. **Local tensor-network codes.** *arXiv* 2109.11996 (2021)

FINDING QUVIGINTS IN A QUANTUM TREASURE MAP[1]

EQUS researchers have developed a method for measuring unknown, high-dimensional quantum states quickly and accurately using machine learning.

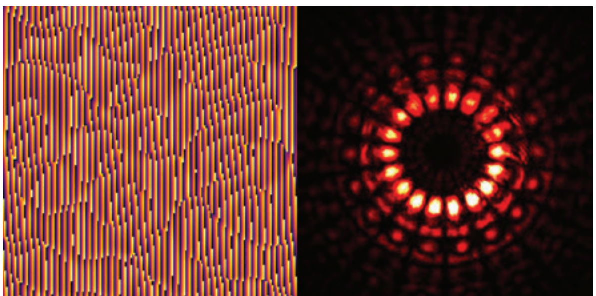
This paper is the first to use the term 'quvigint', meaning the team have also created a new word!

DEFINITIONS

A **quvigint** is like a qubit (the quantum version of a classical bit that takes on the values '0' or '1'), except that it takes on not two, but 20 possible values.

High-dimensional quantum states are ideal for storing and sending large amounts of information securely. However, measuring unknown states becomes increasingly difficult in higher dimensions, because the same scaling that gives quantum devices their power also limits our ability to describe them.

One way of thinking about this problem is to imagine navigating a high-dimensional quantum treasure map. Using standard quantum-state tomography, the treasure (the unknown state) would be identified by first determining which directions you need to look in to ensure you cover the whole map (determining an orthogonal basis), then collecting and storing all the relevant data, and finally processing the data to find the treasure.



Hologram encoding a quvigint (left), such as that photographed during the experiment (right)
Image by Markus Rambach

Instead, using self-guided quantum-state tomography, two search directions are chosen at random and tested. The one that gets you closer to the treasure, based on clues from the machine learning algorithm, is selected and the other discarded. These steps are then repeated until the treasure is found. Self-guided tomography thus saves a huge amount of time and energy, allowing the unknown quantum state to be found much more quickly and easily.

To illustrate the technique, the EQUS team simulated a quvigint (a 20-dimensional quantum state) travelling through the atmosphere, as it would when being used to send quantum information between two points on Earth or to a satellite. As the quvigint travels, it is modified by atmospheric turbulence. Standard tomography is very susceptible to this type of noise, but by using self-guided tomography the team were able to reconstruct the original quvigint with high accuracy.

Unlike other methods for classifying unknown quantum states, self-guided tomography is efficient, accurate, robust to noise and readily scalable to high dimensions, such as quvigints. Because it is agnostic to the physical system, it may also be applied to other systems such as atoms or ions.

1 M Rambach, M Qaryan, M Kewming, C Ferrie, AG White & J Romero. **Robust and efficient high-dimensional quantum state tomography.** *Phys. Rev. Lett.* 126:100402 (2021)

Designer quantum materials

2022 ACTIVITY PLAN

- Assemble all functional components of a linear ion-trap system to directly implement quantum simulations of chemical dynamics
- Conduct experiments on solid immersion lenses embedded in fibre cavities for enhanced polariton–polariton interactions
- Demonstrate quantum advantage on shared randomness processing using transverse spatial modes
- Measure off-resonantly pumped cavity exciton polaritons
- Test erbium materials and cavity-coupling architectures for quantum networks
- Test qudit gates based on multiplane light conversion on single photons

Quantum-enabled diagnostics and imaging

Sensors are ubiquitous in modern technology, enabling examination of human bodies, the environment, galaxies and more. The Quantum-Enabled Diagnostics and Imaging program uses quantum mechanics to engineer new probes, sensors and techniques to enhance capabilities across a range of applications, including medical imaging and navigation.

2021 HIGHLIGHTS

In 2021, EQUS researchers made substantial progress in this program in the development of engineered optomechanical devices, the use of quantum physics for probing biological systems, many-body spin states for sensing and new approaches to tests of fundamental physics.

Key advances are as follows:

Experimental platforms

- High-frequency gravitational-wave detector and observation of two rare events
- Quantum-enhanced microscopy for high-resolution in vivo imaging of biological systems (see page 29)
- Searches for ultralight and light dark matter using interferometric and crystal-based oscillator methods

Theoretical advances

- Evasion of quantum measurement backaction on mechanical oscillators, enabling detection and estimation of weak forces and the creation and measurement of nonclassical motional states of the oscillator
- Protocol to perform robust quantum sensing within quantum error-correction codes
- Theoretical proposal for an advanced laser threshold magnetometry scheme using Raman lasers in diamond (see page 30)

A MICROSCOPE THAT CAN SEE THE IMPOSSIBLE[1]

EQUS researchers have demonstrated absolute quantum advantage in microscopy, creating a quantum microscope that can image biological structures with high resolution, without harming them.

The performance of light-based microscopes is limited by the stochastic nature of light. Increasing the intensity of the light being used improves the performance, but the intensity can be increased only so much without damaging the sample. This photodamage limit is especially relevant for fragile samples, such as human cells, which incur damage at relatively low intensities.

The EQUS team built a stimulated Raman microscope that uses quantum entanglement to evade photodamage. By suppressing noise, entanglement improves imaging performance for a given intensity of laser. The team's quantum-enhanced microscope thus enables the observation of biological structures that could not otherwise be resolved.

(Left to right) Waleed Muhammad, Catxere Casacio, Warwick Bowen and Lars Madsen aligning the quantum microscope

As a demonstration, the team imaged molecular vibrations in a yeast cell with 200-nanometre resolution (sufficient to clearly distinguish different regions within the cell), without destroying it. This corresponds to a 35% improvement in clarity, or 14% improvement in concentration sensitivity, compared with classical microscopy.

Better imaging will enable better understanding of living systems and improved diagnostic technologies. The team's result thus paves the way for applications in biotechnology and could lead to the development of new technologies in other fields that rely on precision sensing, such as navigation and gravitational-wave detection.

Although absolute quantum advantage has previously been demonstrated in communication and computing, this result is the first demonstration of absolute quantum advantage in sensing.

DEFINITIONS

Entanglement, or 'spooky action at a distance', is a phenomenon whereby quantum systems may retain some connection or dependence even when separated by a large distance.

Quantum advantage is the idea that, by exploiting quantum effects, some devices or applications may be improved beyond what would be possible using only classical effects, not only today (given current technology and knowledge) but ever.

The **photodamage limit** of a sample refers to the intensity of light it can tolerate before being damaged. Without quantum effects, the only way to improve the performance of light-based microscopes is to increase the intensity of the light; the photodamage limit thus places a fundamental limit on the performance of classical microscopes.

1 CA Casacio, LS Madsen, A Terrasson, M Waleed, K Barnscheidt, B Hage, MA Taylor & WP Bowen. **Quantum-enhanced nonlinear microscopy.** *Nature* 594:201–206 (2021)

PRECISION MAGNETOMETRY WITH DIAMOND[1]

EQUS researchers have proposed a high-sensitivity magnetometry scheme based on a diamond Raman laser with visible pump absorption by nitrogen-vacancy centres in the same diamond crystal.

Magnetic-field sensing is important in many industries. One proposal for precision sensing is visible-wavelength laser threshold magnetometry. The original proposal for this is based on a continuous-wave diamond nitrogen-vacancy spin laser, but has yet to be realised experimentally.

This work was supported by an EQUS Collaboration Grant awarded to Sarath Raman Nair that enabled him to visit Dr Jan Jeske at the Fraunhofer Institute for Applied Solid State Physics in Germany.

DEFINITIONS

A **nitrogen-vacancy centre** is a type of impurity or defect in diamond, whereby (a very small number of) nitrogen atoms appear in the otherwise purely carbon crystal lattice. Owing to the atomic/electronic structure of nitrogen and carbon, each nitrogen impurity is accompanied by a neighbouring vacancy in the lattice. Together, these create the nitrogen-vacancy centre.

A **Raman laser** is a type of laser based on stimulated Raman scattering, whereby incident photons transfer (vibrational) energy to a gain material.

The EQUS team investigated laser threshold magnetometry instead using the well-established visible-wavelength diamond-crystal Raman laser, which makes it more experimentally plausible. They proposed a conceptually simple and highly sensitive room-temperature quantum magnetic sensor that combines a diamond-crystal Raman laser and nitrogen-vacancy defect spins in the same crystal. The magnetic field is sensed by looking at the output from the Raman laser, which varies because of the magnetic-field-dependent optical absorption of the laser's pump by nitrogen-vacancy spins.

Their results show the experimental feasibility of the magnetic sensor for room-temperature applications such as mineral exploration and navigation. The next step is to realise the idea experimentally, enabling the team to explore the sensing capabilities of a chip-scale diamond Raman laser.

Glowing diamond: when a green light is shined into a diamond containing nitrogen-vacancy centres, it glows red
Image by Jemy Geordy

1 S Raman Nair, LJ Rogers, DJ Spence, RP Mildren, F Jelezko, AD Greentree, T Volz & J Jeske. **Absorptive laser threshold magnetometry: combining visible diamond Raman lasers and nitrogen-vacancy centres.** *Mater. Quantum Technol.* 1:025003 (2021)

Quantum-enabled diagnostics and imaging

2022 ACTIVITY PLAN

- Apply sophisticated signal-processing tools to solid-state sensing platforms to enable detection of forces beyond conventional quantum limits and investigate the use of such platforms for experiments on quantum gravity
- Continue to use precision optomechanics to test fundamental physics, such as searches for high-frequency gravitational waves and tests of quantum gravity
- Demonstrate the possibility of realising a bulk-acoustic-wave quantum clock
- Extend bioimaging capability to multispectral microscopy and dynamic viscosity
- Optimise single-photon counters for axion dark-matter detection and continue axion dark-matter experiments such as ORGAN and UPLOAD
- Progress experiments on the realisation of a compact nitrogen–vacancy maser platform, explore its use as a magnetic-field sensor and precision oscillator, and investigate its sensitivity to external effects

Quantum engines and instruments

The Quantum Engines and Instruments program develops tools and design approaches that enable complex quantum machines to be pieced together from disparate components. It aims to pioneer a new generation of instruments tailored to the demanding requirements of quantum science, including precision clocks, oscillators and time bases, and high-speed cryogenic electronics.

2021 HIGHLIGHTS

In 2021, EQUS researchers made progress in this program in areas such as atomtronics, superconducting and optical systems and devices, nuclear spin isomer characterisation, benchmarking tools, quantum thermodynamics and engines, and dark-matter detection.

Key advances are as follows:

Experimental platforms

- Compact absolute laser-frequency reference for future space missions (see page 34)
- Single-photon detectors at microwave and telecommunications wavelengths, with ongoing efforts to reduce noise and fluctuations
- Terahertz scanning near-field optical microscopy for non-invasive characterisation of superconducting quantum devices (see page 33)

Theoretical advances

- Benchmarking tools for the next generation of two- and three-qubit devices and for near-term industrial quantum devices
- Development of the theory of superconducting circulators and validation against experiments
- Identification of a lower bound for entropy production in continuously measured, zero-temperature quantum systems

NON-DESTRUCTIVE NANOSCOPY FOR IMPROVED QUANTUM DEVICES[1]

EQUS researchers have developed a non-destructive method for identifying and addressing imperfections that lead to decoherence in superconducting quantum devices.

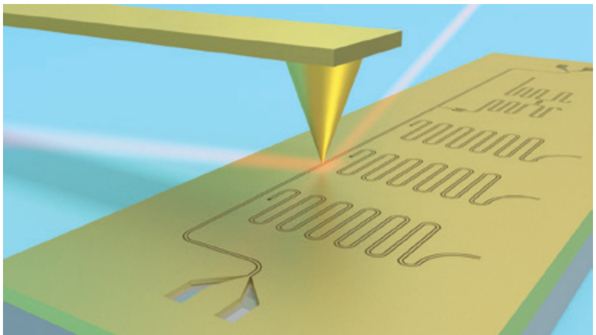
Superconducting quantum circuits are one of the most promising technologies for commercial quantum computing, attracting interest from industry giants such as Google and IBM. But widespread application of this technology is hindered by decoherence, which causes information to be lost from the devices.

The interdisciplinary team used terahertz scanning near-field optical microscopy (THz SNOM) to probe superconducting quantum devices. This technique combines high spatial resolution and local spectroscopic measurements, providing detailed information about the topography of the device and its material properties.

The team showed that common techniques for fabricating superconducting circuits on silicon chips unintentionally introduce imperfections in the devices that lead to decoherence. They also showed that surface treatments reduce these imperfections.

In contrast to other methods, which often require the devices to be cut up before being probed, THz SNOM is non-destructive, meaning the same device may be probed multiple times during the fabrication process. This allowed the team to determine where in the process defects were introduced and optimise fabrication protocols.

By identifying a key source of loss (decoherence) and developing ways to address it, the team's results provide a path towards improving superconducting devices for use in quantum computing applications. In future, THz SNOM could be used to improve understanding of other loss channels and how to control or eliminate them.



Schematic of a superconducting circuit on a silicon chip being imaged using THz SNOM

This article, published in August 2021, was the ninth-most-read feature article in *Applied Physics Letters* for 2020–21, with nearly 2,000 downloads.

DEFINITIONS

Decoherence refers to the (detrimental) loss of information from a quantum system due to interactions between the system and its environment.

Terahertz scanning near-field optical microscopy (THz SNOM) provides a way to image the surfaces of samples with nanometre-scale spatial resolution (seeing down to the size of viruses). It involves focusing light onto the metallic tip of an atomic force microscope, which then 'reads' or 'feels' the surface of the sample similarly to the stylus on a record player. By using terahertz-frequency (rather than visible or infrared) light, information about the material properties below the tip of the microscope is obtained, in addition to the surface topography. This information (specifically, the number of charge carriers or the local electrical conductivity) enables differentiation between metallic and semiconducting regions.

1 X Guo, X He, Z Degnan, BC Donose, K Bertling, A Fedorov, AD Rakić & P Jacobson. **Near-field terahertz nanoscopy of coplanar microwave resonators.** *Appl. Phys. Lett.* 119:091101 (2021)

LASER-FREQUENCY STABILITY FOR NEXT-GENERATION GEODESY MISSIONS[1]

EQUS researchers have developed a compact absolute laser-frequency reference for future space-based geodesy missions.

Satellite-based geodesy relies on inter-spacecraft laser interferometry. To accurately track climate-induced movements of water and ice around Earth over long timescales (months to decades), ranging measurements require long-term absolute laser-frequency stability to calibrate the data.

The EQUS team have investigated a technique to provide long-term absolute laser-frequency data for future space-based gravity missions (such as GRACE and GRACE Follow-On) with minimal changes to existing flight-qualified hardware. The simple and robust technique applies additional gigahertz modulation to the laser, revealing information about the length of an optical cavity. This information is then used to correct for changes in laser frequency over time.

This result represents an enabling technology for laser interferometry on future space-based gravity-sensing missions, the next of which is expected to launch within the decade. The next step is to test and validate the technique to ensure the readout scheme is ready for inclusion in the next mission.

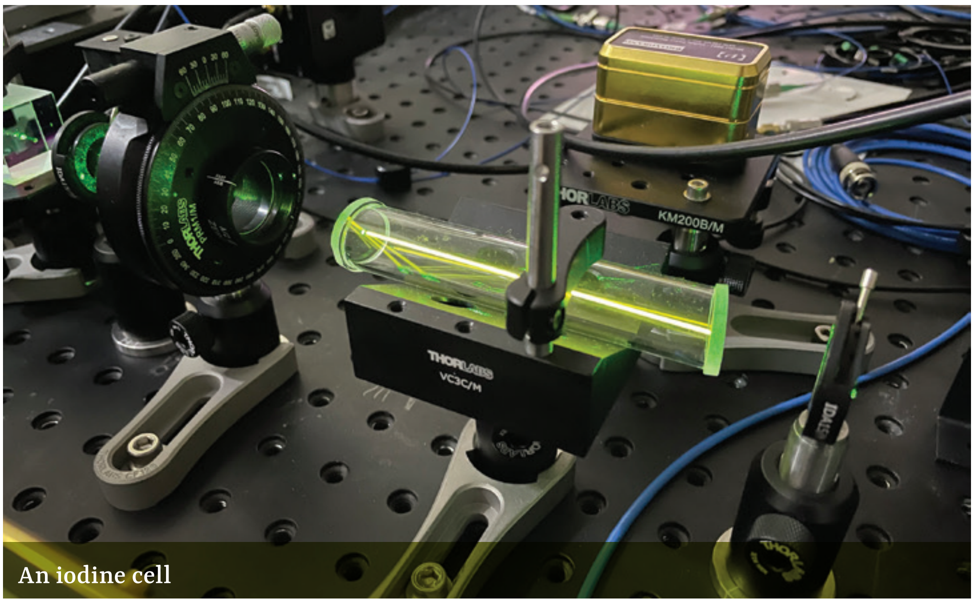
Chief Investigator Kirk McKenzie helped to build the satellites for the GRACE Follow-On mission, while working at NASA's Jet Propulsion Laboratory.

A prototype of the team's system is being developed in collaboration with CEA Technologies and NASA, with support from an Australian Space Agency Grant and the ARC Centre for Excellence for Gravitational Wave Discovery. In 2021, EQUS funded a research translation project to upgrade flight-like test capability for this prototype (see page 42).

DEFINITIONS

Geodesy is the science of Earth's shape, orientation and gravity.

A **laser interferometer** is a sensing device based on the interference of light. A laser beam is split in two, sent on different paths and then recombined. The behaviour, or interference pattern, of the combined light provides information about various phenomena, such as changes in Earth's local gravity.



An iodine cell

1 ER Rees, AR Wade, AJ Sutton, RE Spero, DA Shaddock & K McKenzie. **Absolute frequency readout derived from ULE cavity for next generation geodesy missions.** *Opt. Express* 29:26014–26027 (2021)

Quantum engines and instruments

2022 ACTIVITY PLAN

- Continue probing the quantum limits of ultralow-optical-power phase tracking and compare high-fidelity simulations to laboratory optical systems
- Continue theoretical efforts on understanding quantum advantage in many-body quantum heat engines, superfluid circuitry, non-equilibrium steady states and quantum gas engines
- Continue work on random benchmarking
- Explore new materials and surface treatments to increase coherence of quantum devices
- Investigate non-Markovian noise in superconducting multiqubit devices and use machine learning methods for noise mitigation
- Start work on quantum and relativistic thermodynamics

1kQubit flagship

The 1kQubit Flagship aims to develop the theoretical foundations for a useful fault-tolerant quantum processor. Such a device requires around 1,000 logical qubits to be built, using around 1,000 physical qubits and based on technology that is expected to be available in the next five to ten years.

This theory-focused flagship, which emerged from the Designer Quantum Materials research program, launched at the start of 2021. It has three main streams:

1. Next-generation qubits
2. Practical high-rate codes and fault-tolerant logic gates
3. High-threshold efficient decoders

2021 HIGHLIGHTS

Although progress towards this flagship was hampered by the departure from EQUS of several key researchers, we have already seen many great results, including:

- Demonstration of how to apply well-known concepts and approximations from classical physics to quantum systems
- Development of the XZZX surface code and of a practical proposal for fault-tolerant quantum error correction (see page 37)
- Development of low-overhead approaches to quantum error correction and fault-tolerant quantum computing using LDPC codes (see page 37)

2022 ACTIVITY PLAN

- Develop practical gates and measurements, and efficient theoretical and numerical descriptions for GKP codes, including a new state preparation scheme
- Develop time-dependent theories of relevant concepts and approximations
- Further develop LDPC codes for quantum hardware with long-range coupling
- Investigate gates in new qubit designs and bias-preserving gates in qudit systems
- Simulate error correction for next-generation qubits using bosonic encodings

NEW ERROR-CORRECTING CODES FOR FAULT-TOLERANT QUANTUM COMPUTING[1,2,3]

EQUS researchers have developed low-overhead approaches to implementing logic gates with qubits protected by error-correcting codes.

Quantum computers will require fault-tolerant architectures based on quantum error-correction codes to mitigate the high levels of noise present in quantum hardware. The idea is to arrange qubits in such a way that if some break or go wrong while performing a computation, they can be corrected using an appropriate code. The most common architecture is based on a code known as the surface code, but this code comes with a high overhead, meaning a very large number of physical qubits and gates are needed to achieve the required performance.

The EQUS team made a small tweak to the conventional surface code, corresponding to a local change of basis (a rotation of every second qubit). They showed that architectures based on the new code, called the XZZX surface code, have much higher memory thresholds and lower overheads than those based on conventional surface codes. The thresholds achieved seem to approach the theoretical limits, and even exceed them, hinting at the enticing possibility of performance improvements beyond what was previously thought possible. Even lower overheads could be achieved by integrating the benefits of the XZZX surface code with codes and architectures with naturally lower overheads, such as low-density parity check (LDPC) codes.

Building on this work, the team developed a scheme for fault-tolerant quantum computing with noise-biased Kerr-cat qubits. They conducted detailed simulations on error correction with Kerr-cat qubits and the XZZX code and are now investigating gates with this proposal. Encouragingly, their proposal may be realised with apparatus currently under development by collaborators at Yale.

Ben Brown and Pablo Bonilla received the EQUS award for Best Contribution to Public Debate for the media coverage of their work on the XZZX surface code. They featured in an ABC News story, with the associated video viewed 110,000 times on YouTube. They were also interviewed by Studio 10.

In separate work, the EQUS team developed a scheme for fault-tolerant quantum computation based on LDPC codes. LDPC codes allow for long-range (not only local) interactions between qubits, meaning a large number of logical qubits may be encoded with only a small number of physical qubits. They showed that quantum gates implemented in such non-local error-correction codes preserve the error-correcting properties of LDPC codes while maintaining the low overheads that make LDPC codes attractive.

1 JP Bonilla Ataides, DK Tuckett, SD Bartlett, ST Flammia & BJ Brown. **The XZZX surface code.** *Nat. Commun.* 12:2172 (2021)
2 AS Darmawan, BJ Brown, AL Grimsmo, DK Tuckett & S Puri. **Practical quantum error correction with the XZZX code and Kerr-cat qubits.** *PRX Quantum* 2:030345 (2021)
3 LZ Cohen, IK Kim, SD Bartlett & BJ Brown. **Low-overhead fault-tolerant quantum computing using long-range connectivity.** *arXiv* 2110.10794 (2021)

Quantum clock flagship

The Quantum Clock Flagship aims to develop the hardware, architecture and theoretical foundations for improved clock technologies. New clock and microwave synthesis hardware and quantum-information-inspired characterisation techniques will enable improved qubit performance metrics and clock-characterisation routines.

This flagship, which emerged from the Quantum Engines and Instruments research program, launched at the start of 2021. It has three main streams:

1. Development of a microwave qubit–clock synthesis chain
2. Investigation of hybrid oscillators based on optomechanical platforms coupled to strain-controlled defects
3. Theoretical exploration of coherent quantum feedback based on incommensurate observables for new oscillator designs

2021 HIGHLIGHTS

Progress towards this flagship was hampered by the COVID-19 pandemic, which prevented the acquisition of relevant people and equipment. Nevertheless, highlights from 2021 include:

- Derivation of a class of quantum states that are optimal for quantum clocks to retain maximal coherence in path and the internal degrees of freedom, and investigation of the effect of noise on this coherence (see page 39)
- Exploration of nuclear spin and hybrid electron–nuclear clock transitions in rare-earth-ion hosts
- Improvement of single-qubit gate fidelity, resulting in an extended system coherence time, using an ultralow-phase-noise synthesis system

2022 ACTIVITY PLAN

- Develop a general system for experiments on frequency stability
- Develop mechanical oscillators coupled to erbium ions as a basis for a rare-earth-ion hybrid oscillator
- Machine and test high-quality-factor mechanical and electromagnetic cavities
- Upgrade the frequency synthesis chain of the ion-trap experiments to improve the flexibility of programming and the ability to run long-gate-sequence experiments, and to integrate a high-power, ultralow-noise amplifier
- Push the theory of hybrid clocks

A FRAMEWORK FOR TESTS OF QUANTUM GRAVITY[1]

EQUS researchers have developed a general framework for testing relativistic effects in quantum systems affected by noise, providing a theoretical foundation for future experiments on quantum gravity.

Clocks, as timekeeping devices, are susceptible to the effects of general relativity. A clock near Earth's surface therefore ticks slower than one far away from it (such as on a satellite)—an effect known as time dilation. Driven by recent developments in quantum technologies, quantum clocks have emerged as ultraprecise timekeeping machines, suitable for testing genuinely relativistic effects. Interferometry with clocks thus provides a potential new way to test relativistic effects. However, realising such tests experimentally is challenging, because of quantum noise.

The EQUS team built on the idea of using quantum clocks to measure time dilation due to gravity. They constructed a general formalism to consider clocks affected by quantum noise (such as when the environment has non-zero temperature) in an interferometry scenario compatible with relativistic time dilation. Although there are many existing models for studying the effect of noise on a quantum particle, translating them to scenarios with time dilation is challenging because time dilation affects all physical processes, including the dynamics of the environment and its interaction with the clock.

The team modelled a quantum clock as a quantum particle with an internal structure, such as an atom and its energy spectrum, and considered an interferometry experiment in which the quantum particle (clock) is prepared in a spatial superposition. The interference of the clock's path reduces the 'visibility' of the interference pattern, demonstrating the relativistic effect of time dilation due to the internal structure of the particle working as a clock.

DEFINITIONS

A **quantum clock** is a clock that uses quantum states of matter or quantum phenomena such as superposition or entanglement for timekeeping, with improved performance compared to classical clocks

Superposition is a fundamental property of quantum mechanics whereby a quantum system takes on two (or more) states simultaneously, until the system is measured or observed, revealing only one state. A **spatial superposition** refers to a quantum system being in two places at once (until it is measured and found in one of the two places).

Their analysis and framework provide tools to better estimate the expected outcome in future interferometry experiments to study relativistic time dilation. The results also provide a general framework for testing other proposals. For example, in an interferometer, a particle simultaneously interacts with two different environments or with a single environment in a state that depends on the path taken. Therefore, it might be possible to probe the properties of two different environments or of environmental parameters such as temperature using a single probe.

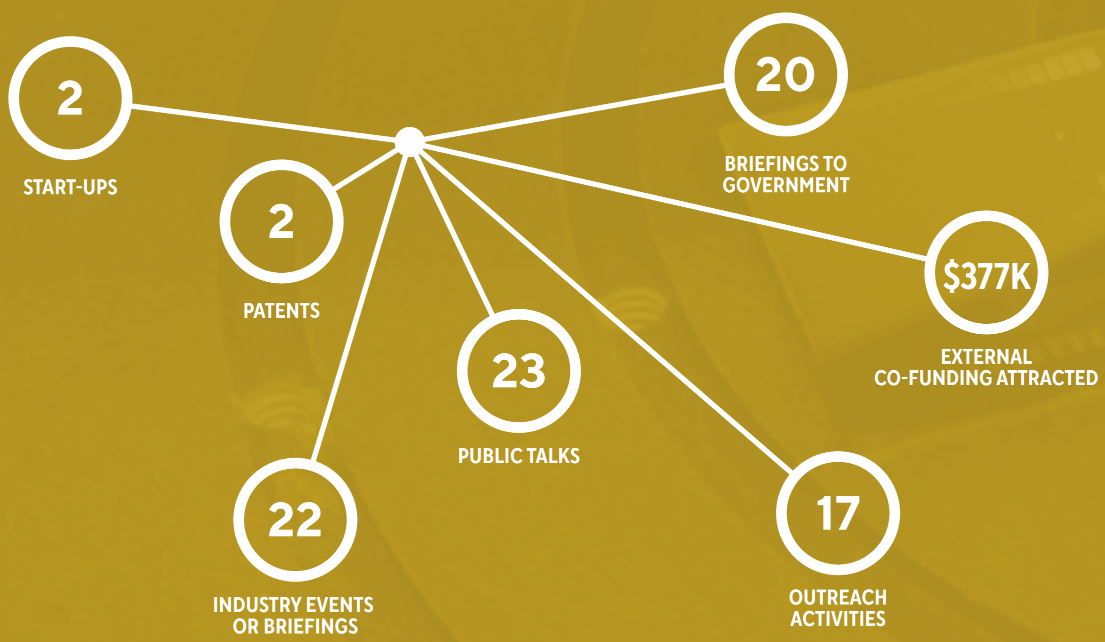
1 H Verma, M Zych & F Costa. **Effect of environment on the interferometry of clocks.** *Quantum* 5:525 (2021)

Our impact: Overview

To complement our cutting-edge research programs, EQUS delivers broad impact through the following:

1. **Research translation**
2. **Equity, diversity and inclusion**
3. **Mentoring and career development**
4. **Outreach and education**

Our capacity-building programs are training a new generation of scientists in cutting-edge fundamental research, innovation and entrepreneurialism. The EQUS team works with partners in government and industry to translate research discoveries into practical applications and devices. We have programs to develop resources for students and teachers, and to inspire future quantum scientists and engineers. We aim to be equitable and inclusive across all our programs, creating an environment that promotes and celebrates diversity and individuality.



Research translation

Translating research outcomes and knowledge into new quantum technologies and applications

Equity, diversity and inclusion

Building a vibrant, engaged, diverse and inclusive community of knowledge leaders for academia and industry

Mentoring and career development

Creating a quantum-literate ecosystem by training a generation of quantum scientists and engineers

Outreach and education

Engaging and educating diverse audiences in quantum science and technology and its potential for our future

Research translation

EQUS is building the foundations for an innovative, advanced economy in Australia. We aim to bridge the innovation gap for the translation of quantum science to quantum technology development, through links with end-users in government, local small-to-medium enterprises and global technology giants.

2021 SUMMARY

The following translation projects were funded in 2021:

Scale-factor unit validation system ANU

NASA's Mass Change Mission, projected to launch in 2025, will monitor climate change signals such as glacial ice melt by their effect on Earth's gravity. This is done using a laser interferometer with nanometre-scale precision, with long-term changes in the wavelength of the laser tracked by a scale-factor unit. In partnership with Australian space hardware company CEA Technologies and EQUS start-up Liquid Instruments, this project aims to develop a portable space-flight-representative testbed for a hardware prototype of a scale-factor unit. This testbed is essential for real-time functional and performance verification during space-flight qualification tests. The project will hopefully lead to a future partnership with NASA, providing Australian laser technology to the Mass Change Mission.

Countermeasures to quantum key distribution UQ

Quantum key distribution satellites allow distant users to exchange messages with each other via an unhackable communications link. Part of the 2021 Australian Army Quantum Technology Challenge, this project demonstrates the feasibility of a field-deployable system to disrupt satellite-mediated quantum key distribution. Portable, ground-based terminals could, in principle, transmit signals that interfere with the sensitive detectors that receive the quantum key which is then used to encrypt and secure the communications channel. Work is ongoing to further develop and potentially commercialise this invention.

Low-phase-noise sapphire clock UWA

In partnership with CryoClock, this project aims to develop and build precision timing hardware. Quantum devices such as atomic clocks and qubits require high-stability, low-noise probe fields. Such low-noise oscillators are also vital components in radar, timing and communication networks. This project involves developing a low-noise, room-temperature oscillator using interferometric microwave phase detection and building a low-phase-noise oscillator based on a cryogenic sapphire cavity, using the principle of noise suppression with a cryogenic resonator.

Navigation Doppler LiDAR ANU

Navigation Doppler LiDAR measures the three-dimensional velocity of a moving object, producing extremely precise, instantaneous positional information about the object for a known starting location. Combined with a conventional inertial navigation system, navigation Doppler LiDAR enables continuous correction for position drift, increasing position certainty over extended periods of time when the Global Navigation Satellite System is unavailable. This project aims to build a proof-of-concept device to generate data on the capability and performance of navigation Doppler LiDAR and to provide validation to various potential markets for subsequent commercialisation.

Quantum computer balance of systems UQ

Candidate hardware platforms for commercial quantum computers are now being deployed, but not at scale. Although much effort is being expended on the details of qubit architecture, control, error correction, and so on, there has been less focus on understanding, engineering and, where necessary, inventing the balance of systems required for a functioning quantum computer. This project involves reviewing the current commercial implementations of quantum computer hardware and undertaking a desktop analysis of the balance of system requirements. It aims to highlight key areas of research and industry development needed to produce the tools for a commercially viable quantum computer.

Novel nitrogen–vacancy centre maser MQ

Masers provide very precise standards for timekeeping and navigation, but conventionally have large technical overheads due to cooling and/or vacuum requirements and are not easily portable. This project aims to build a compact and frequency-tunable room-temperature maser platform using nitrogen–vacancy centres in diamond, with applications in timekeeping and defence. As a field-deployable precision magnetometer, such a device has applications including navigation in GPS-denied environments, imaging of biological systems and infrastructure building.

2022 ACTIVITY PLAN

EQUS will continue to encourage and support research translation activities in 2022. Projects expected to receive funding include:

Hydrogen spin-isomer sensors UQ, UWA

The lowest energy levels of the two nuclear spin isomers of hydrogen (ortho- and para-) differ by more than the heat of vaporisation. In liquid hydrogen, ortho-hydrogen spontaneously converts to para-hydrogen, releasing enough energy to boil off a substantial amount of the liquid. For economic and safety reasons, it is therefore important to know the ratio of spin isomers in liquid hydrogen during commercial storage and transport. This project will use Raman spectroscopy and microwave cavities to measure this ratio, with the goal of installing prototype sensors on industrial plants for field trials.

Quantum link verification UQ

This project aims to commercialise a method for using quantum resources for zero-trust verification of physical-layer security for a classical communications channel.

Non-contact weighbridge UQ

As a follow-on to the 2021 Ascend program, this project will develop technologies for measuring the mass of large objects (such as trains, ships and silos) without having to touch them.

A FIELD-DEPLOYABLE PRECISION MAGNETOMETER

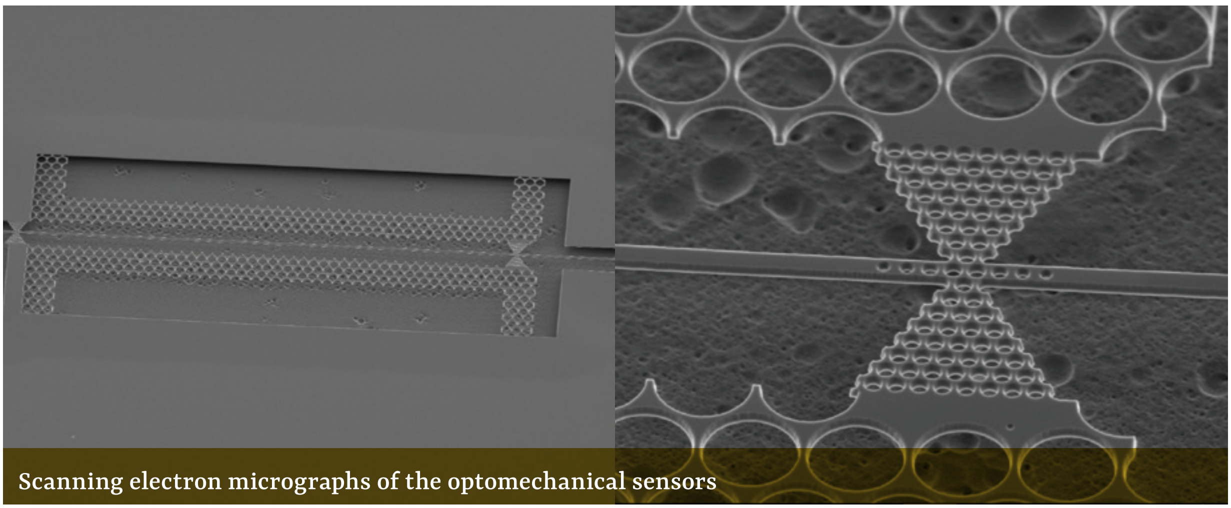
In 2020, EQUS' Translational Research Program awarded $56,000 to a project to develop optomechanical magnetometers ready for deployment outside the laboratory. The project was undertaken by Stefan Forstner, in collaboration with other EQUS researchers from the Quantum Optics Laboratory at UQ.

Magnetic-field sensing is important in many industries, including medical imaging, mineral exploration, navigation and defence. Current precision magnetometers require cryogenic cooling, bulky magnetic shielding and/or multi-laser readout, making them unsuitable for use in the field. Optomechanical magnetometers circumvent these challenges, providing state-of-the-art sensitivity at high (megahertz) frequencies. However, to translate the technology out of the laboratory, the frequency bandwidth needs to be extended to lower (hertz and kilohertz) frequencies and the technology needs to be modified to ensure scalability.

This project saw the fabrication of several compact, low-energy precision sensors, including magnetometers and ultrasound sensors, each with successive improvements. It provided a proof-of-concept of a method to suppress the largest source of noise for optical sensors at low frequencies (laser phase noise). The magnetometers were built using a silicon-on-insulator platform and waveguide coupling, which means they are scalable and will integrate with other devices.

Collaborators at Defence Science Technology Group have subsequently functionalised devices for magnetic-field sensing. The next steps are to further improve the magnetic functionality of the devices and to pursue full integration.

The project involved Chief Investigator Warwick Bowen, Research Fellows Stefan Forstner, Erick Romero, Elizabeth Bridge, Glen Harris, James Bennett and Igor Marinkovic, and PhD students Fernando Gotardo and Hamish Greenall.



Scanning electron micrographs of the optomechanical sensors

PASSIVE SUPERCONDUCTING ON-CHIP MICROWAVE CIRCULATOR

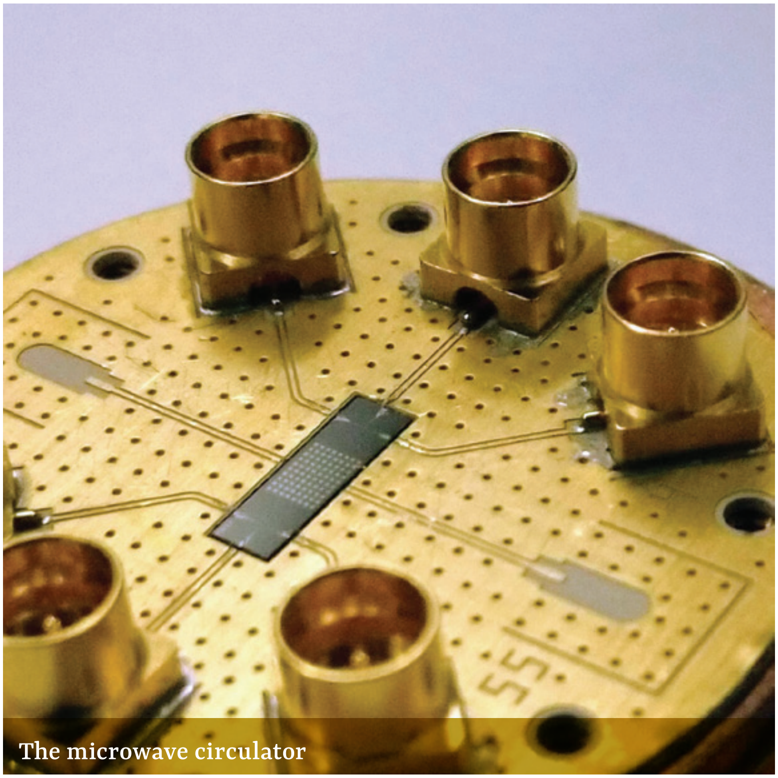
In 2020, EQUS' Translational Research Program awarded $53,000 to a project to design a compact and integrated superconducting microwave circulator. The project was a collaboration between theorists and experimentalists, led by Tom Stace, Arkady Fedorov and Rohit Navarathna.

In electronic circuits, circulators route signals from one port to the next in a cyclic manner. They are also used as isolators, sending signals in one direction, while blocking signals from the opposite direction. Conventional circulators are big and bulky, require cryogenic cooling and use permanent magnets that interfere with superconducting circuits.

This project saw the development of a compact, integrated superconducting microwave circulator. Based on the lossless properties of superconductors, the technology is inherently compatible with other superconducting circuits. This allows the circuit to be on the same chip as other superconducting hardware, simplifying the integration, fabrication and operation of superconducting quantum processors. Because the on-chip circulator uses Josephson junctions, which are much smaller than the wavelength of the microwaves, the size limitation of conventional circulators is overcome. Although the on-chip circulator still requires a magnetic field through the ring of junctions, the magnitude of the field is much smaller than in conventional circulators, ensuring the superconductivity is not destroyed.

The project led to a deeper understanding of the problems with charge-sensitive devices and of the theory of superconducting circulators. Measurements of the outputs of the device reveal circulation, with a controllable, slow quasiparticle tunnelling rate. The technology has since been licensed via UQ to EQUS start-up Analogue Quantum Circuits.

This project was a collaboration between Chief Investigators Tom Stace and Arkady Fedorov, PhD students Dat Thanh Le, Rohit Navarathna and Andrés Rosario Hamann, and Associate Investigator Clemens Müller.


The microwave circulator

Equity, diversity and inclusion

EQUS is committed to improving equity, diversity and inclusion within the Centre and the wider quantum physics community. We aim to foster a safe, welcoming and inclusive environment that allows all EQUS members to achieve success and to feel respected and supported.

2021 SUMMARY

Centre activities in 2021 related to equity, diversity and inclusion include:

- Introduction of guidelines for writing inclusive position descriptions
- Virtual screening and discussion of In My Blood It Runs in recognition of Harmony Week, organised by PhD student Amy Navarathna
- Journal club on queering science communication in recognition of International Day Against Homophobia, Biphobia, Intersexism and Transphobia (IDAHOBIT), led by Research Fellow Tara Roberson

Kumospace set-up for LGBTQIA+ STEM Day

- Virtual gathering in recognition of LGBTQIA+ STEM Day, led by Chief Investigator Andrew Doherty
- Sponsorship of LGBTQIA+ and First Nations scholarships for Science & Technology Australia's Science meets Parliament (see page 47)

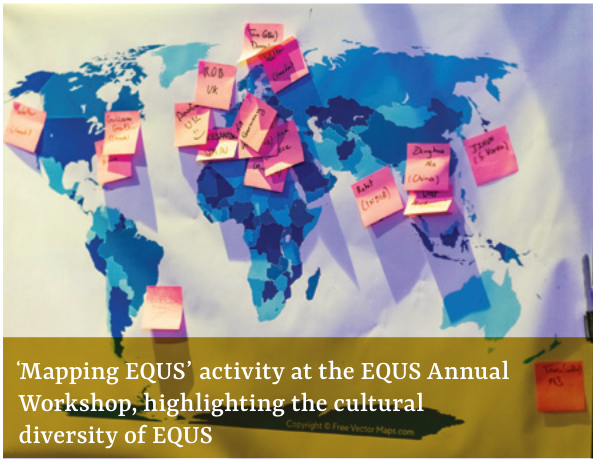
The following initiatives began in 2021 and are ongoing:

- Review of EQUS' primary carer and re-entry awards to ensure they best meet the needs of EQUS members
- Development of improved grievance-reporting policies and procedures to ensure unwanted behaviours are appropriately identified and addressed
- Planning and implementation of a networking event for people from underrepresented groups in STEM working in a Centre of Excellence
- Implementation of the 2021–22 EQUS summer research program, which provides undergraduate students from underrepresented groups in STEM the opportunity to undertake a defined research project and participate in development activities

2022 ACTIVITY PLAN

In addition to continuing ongoing activities, in 2022 the Centre plans to start work on the following initiatives:

- Expansion of the guidelines for inclusive position descriptions to other aspects of recruitment
- Scholarships for higher-degree research students from underrepresented groups in STEM
- Funding for women-only postdoctoral research fellowships (Deborah Jin Fellowships)
- Training for Centre members and Centre leadership in relation to equity, diversity and inclusion



'Mapping EQUS' activity at the EQUS Annual Workshop, highlighting the cultural diversity of EQUS

FIRST NATIONS AND LGBTQIA+ SCHOLARSHIPS FOR SCIENCE MEETS PARLIAMENT

EQUS is proud to continue to sponsor events and activities that promote equity, diversity and inclusion within the STEM community. In 2021, the Centre once again sponsored scholarships for people identifying as First Nations or LGBTQIA+ to attend Science & Technology Australia's Science Meets Parliament event.

"As Science Meets Parliament 2021 draws to a close, I've enjoyed reflecting on what an incredible opportunity it was.

"It was very important for me to have a voice as a member of the LGBTQIA+ community, and to participate in conversations that drive the future of STEM policy in Australia. I want to thank the Australian Research Council Centre of Excellence for Engineered Quantum Systems for this.

"[Science Meets Parliament] facilitated crucial networking and showed me examples of integrating science with policy. I really enjoyed the chance to engage with other driven individuals and be inspired by their drive. Discussions with individuals of many different disciplines allowed us to give fresh perspective to the tasks we tackle as a community. There were also many panels that served as a platform to learn how to be a better advocate for STEM. In particular, I appreciated the poignant reminder to be an ally to Indigenous communities and the very useful recommendations on how to do this effectively.

"I could not have participated in any of this without the scholarship support of EQUS to amplify diverse voices and for this I thank them."

Olivia Jessop, LGBTQIA+ scholarship recipient

Mentoring and career development

EQUS provides training and mentoring for our higher-degree research students and early-career researchers to support the advancement of their research and technical skills, and broader knowledge of the field. Training opportunities also aim to build knowledge and skills in the areas of entrepreneurship and commercialisation, leadership, and media and communications. EQUS members also have access to guidance and support through the Centre's mentoring program.

2021 SUMMARY

Several activities relating to mentoring and career development became virtual or were deferred as a result of the on-going COVID-19 pandemic. Despite this, we successfully delivered several programs and events, including:

- Review and relaunch of the EQUS mentoring program (currently 60 mentees matched with 51 mentors)
- Relaunch of the EQUS seminar series, with 12 seminars covering a range technical and non-technical topics
- Funding for three EQUS teams to participate in the Cruxes Innovations Ascend program
- Python Workshop
- EQUS–FLEET Idea Factory (see page 49)
- Annual Workshop (see pages 50–51)

2022 ACTIVITY PLAN

In 2022, EQUS is aiming to deliver the following training and development activities:

- Grow the mentoring program
- Develop and implement a training plan for EQUS students and early-career researchers
- Summer School
- Idea Factory
- Python Workshop

EQUS Director Andrew White opening the EQUS Annual Workshop in Noosa

2021 EQUS–FLEET IDEA FACTORY

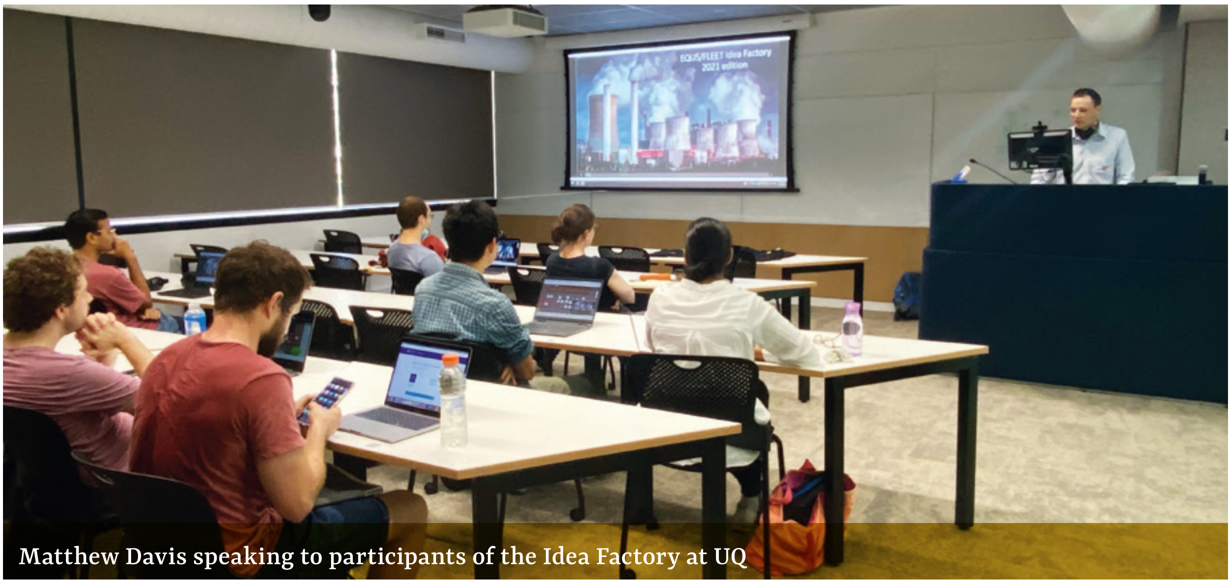
In November, EQUS co-hosted the 2021 Idea Factory with the ARC Centre of Excellence in Future Low-Energy Electronics Technologies (FLEET). Around 30 early-career researchers from across both centres participated in the event, which ran in a hybrid format.

The goal of the 2021 Idea Factory was to provide early-career researchers with the skills and confidence to write a successful research grant. Participants were put into teams and tasked with choosing a research question they could write a short research proposal for and then present, as a 10-minute pitch, to a judging panel.

To help guide them and shape their proposal, attendees heard from Dr Merryn McKinnon, Professor Gerard Milburn, Professor Andrew White and Jesse Vaitkus on the topics of science communication, grant writing and presentation skills. Teams also had access to a group of mentors, including Chief Investigators Magdalena Zych, Halina Rubinsztein-Dunlop and Gavin Brennen.

Chief Investigator Matthew Davis, who led this year's event, said: "The teams put in a lot of work across the three days of the workshop to produce a three-page proposal. The advice from Gerard and Merryn was clearly reflected in their writing and presentations. The winning teams did a spectacular job of communicating their ideas on paper and in presentations with such a short amount of time for preparation."

Congratulations to the winning team: Guillaume Gauthier, Lewis Williamson, Jihun Cha and Harshit Verma. Special commendation was also given to Andrew Groszek, Eric He, Abithaswathi Muniraj Saraswathy, Carolyn Wood and Christina Giarmatzi for their team's presentation.



Matthew Davis speaking to participants of the Idea Factory at UQ

2021 EQUS ANNUAL WORKSHOP

The EQUS Annual Workshop is a key forum for collaboration and exchange of ideas between EQUS members. The 2021 workshop ran as a hybrid event, with talks streamed to venues in Busselton, WA, Noosa, QLD, and Coogee, NSW, as well as to online attendees.

The workshop was attended by roughly 150 people, including students, early-career researchers, Chief Investigators and members of the Scientific Advisory Committee. Highlights of the event include:

- Invited talks by Dr Chelsea Bartram, Professor Lisa Kewley and Professor Päivi Törmä
- Research and portfolio updates from EQUS members
- Pitch, poster and three-minute thesis competitions
- Awarding of EQUS prizes (see pages 12–13)

Dr Chelsea Bartram is an experimentalist at the University of Washington, where she is one of the leaders of the Axion Dark Matter eXperiment (ADMX). As part of a joint session with the ARC Centre of Excellence in Dark Matter Particle Physics, Dr Bartram presented recent results and future plans for ADMX. Several EQUS researchers from the Quantum Technologies and Dark Matter Laboratory at UWA are also part of the ADMX Collaboration.

Professor Lisa Kewley, an ARC Laureate Fellow at ANU and Director of the ARC Centre of Excellence

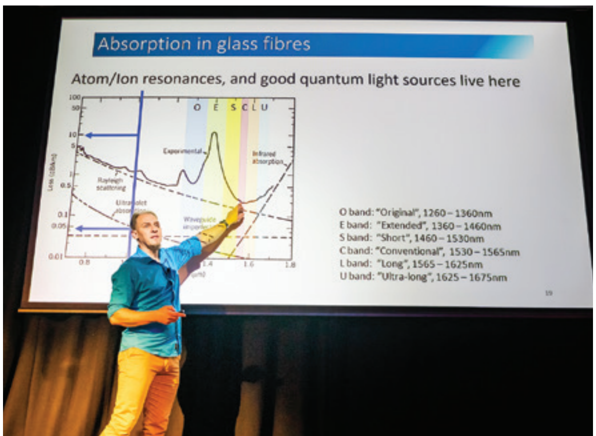
EQUS members at the EQUS Annual Workshop in Busselton

EQUS members at the EQUS Annual Workshop in Coogee

EQUS members at the EQUS Annual Workshop in Noosa

Namisha Chabbra and the ANU team at the EQUS Annual Workshop in Coogee

in All-Sky Astrophysics in 3D (ASTRO3D), presented data and workforce models related to gender balance in STEM in Australia. She also shared strategies that have been implemented successfully at ASTRO3D to create a more diverse academic workforce, such as targeted recruitment and culture change initiatives.



Till Weinhold presenting at the EQUS Annual Workshop in Noosa

Maria Carol Villavedra presenting her poster at the EQUS Annual Workshop in Coogee

Professor Päivi Törmä, from Aalto University in Finland, presented work on quantum geometry, superconductivity and Bose–Einstein condensation, including a connection between superconductivity (superfluidity) and quantum geometry that explains the observation of superconductivity in bilayer graphene, and the experimental realisation of a hybrid Bose–Einstein condensate of surface plasmons and light.

Alongside research and portfolio updates, EQUS students and early-career researchers had the opportunity to share their research in a poster or three-minute thesis (3MT) format or to pitch their research to hypothetical investors. Prizes were awarded to the top presenters in each category. This was the first time the EQUS Annual Workshop featured pitch and 3MT competitions.

The awards dinner was another highlight of the workshop, providing the Centre Executive with an opportunity to acknowledge the outstanding performance of our members and recognise the contributions they make to EQUS.

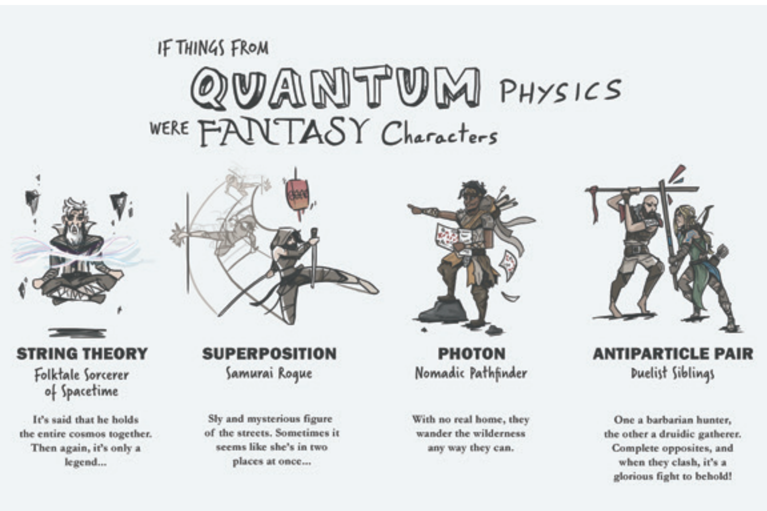
Outreach and education

EQUS continues to engage the community in quantum and its potential for the future of society. We aim to engage and educate the wider community by promoting our research through media releases, the EQUS website and social media. The Centre and its members also participate in public events and activities, collaborations with science teachers and consultations with government and industry.

2021 SUMMARY

In 2021, communication and outreach activities were once again limited by the COVID-19 pandemic. Nonetheless, we delivered a successful program of activities, which included the following:

- Participation as a scientific partner in the Quantum Shorts short-film competition, an initiative of the Centre for Quantum Technologies at the National University of Singapore
- Public screenings of the finalists of Quantum Shorts and Q&A panels in Brisbane and Perth, as well as a virtual screening and Q&A in collaboration with the Sydney Quantum Academy
- Launch of the EQUS podcast Clear as Quantum (see page 53)
- WA Quantum and Dark Matter Road Trip (see pages 54–55)
- Quantum Hackathon
- Quantum Art Competition
- Collaboration with science teachers to develop classroom resources
- Sponsorship of various educational and/or outreach activities undertaken by EQUS members



Winning entry in the 2021 EQUS Quantum Art Competition, an imagination of concepts from quantum physics as characters from a fantasy world, by Toby Davis

2022 ACTIVITY PLAN

The key outreach and education activities planned for 2022 include:

- National Quantum and Dark Matter Road Trip
- Clear as Quantum season 2
- Development of museum exhibits
- Outreach and engagement scholarships
- Sponsorship of relevant activities and initiatives

CLEAR AS QUANTUM PODCAST

In October, EQUS launched a podcast, Clear as Quantum, with the goal of introducing and explaining quantum science and technology to non-experts and inspiring the next generation of quantum scientists and engineers. Season 1 consists of 10 episodes, hosted by Associate Investigator Lachlan Rogers, Research Fellow Elizabeth Bridge and PhD student Yasmine Sfendla, and edited by PhD student Catriona Thomson.

The pilot episode introduces listeners to the hosts; each subsequent episode features an EQUS member talking about a particular keyword, such as 'engineered', 'quantum' or 'systems'. The hosts and guests also discuss paths into quantum science, the future of quantum technology in Australia and the sounds of quantum, including the various sounds of laboratory equipment, the silence of a soundproof laser room, and the soundtrack from The Third Man played on a zither.

The 10 episodes have been downloaded a total of 1,903 times, across 42 countries, with an average of 83 downloads per episode in the first 7 days after release and 157 in the first 60 days. Clear as Quantum is available on all major podcast apps and online.

QUANTUM AND DARK MATTER ROAD TRIP

As part of National Science Week, EQUS researchers piled into a minibus and embarked on a Quantum and Dark Matter Road Trip around southwest Western Australia. Over the five-day trip, the team spoke to nine classes across seven schools and delivered three public events, reaching a total of roughly 1,000 students, teachers and members of the public.

They engaged their audiences through demonstrations such as a water clock and an umbrella-based proof of the existence of dark matter, provided a sneak peek into the lives of physicists, and talked up the cutting-edge research being done at EQUS and the ARC Centre of Excellence in Dark Matter Particle Physics.

Chief Investigator Michael Tobar delivered a public lecture on quantum technology, measuring time, sapphire clocks and the search for elusive dark-matter particles. On display during the talk was a sculpture by local artist Duncan Moon, *Tempus*

Students at Mt Barker Community College exploring an umbrella-based proof of the existence of dark matter

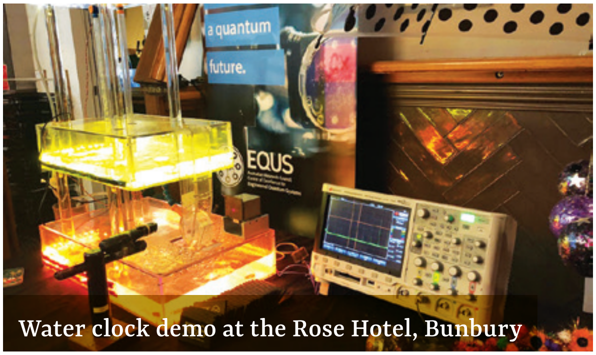
Jeremy Bourhill, Ben McAllister and Michael Tobar at the Newton Moore Senior High School STEM Community Fair

Duncan Moon with his sculpture, *Tempus fugit*, at UWA Albany Campus

Road trip map

fugit, which explores the human perception of time and space.

The team had a stall at the Newton Moore Senior High School STEM Community Fair, during which Associate Investigator Ben McAllister gave a public talk about dark matter and how quantum technologies are being used in dark-matter searches. The team also set up their demonstrations at the Rose Hotel, Bunbury, facilitating fruitful discussions with local punters.



Water clock demo at the Rose Hotel, Bunbury

This initiative was jointly supported by funding from National Science Week Small Grants and the ARC Centre of Excellence for Dark Matter Particle Physics.

Road trip stops:

- Wagin District High School
- Denmark Senior High School
- Mt Barker Community College
- UWA Albany Campus
- Albany Senior High School
- Newton Moore Senior High School
- Dalyellup College
- The Rose Hotel, Bunbury
- Nannup District High School

The WA road trip team (left to right): Michael Tobar, William Campbell, Aaron Quiskamp, Ben McAllister, Elrina Hartman, Catriona Thomson, Cindy Zhao and Jeremy Bourhill

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Key performance indicators

	2021 TARGETS	2021 ACTUALS
RESEARCH OUTPUT AND SERVICE		
Peer-reviewed journal articles	85	100
High-impact publications (in the top 20% most cited papers in fields of physics)	20	55
International and national advisory boards in the research field of the Centre	2	25
Keynote and plenary addresses at international and national conferences	4	7
Editorial boards for international peer-reviewed journals in the research field of the Centre	2	18
Program committees for international and national conferences	10	11
Invited talks or papers at international meetings	25	81
Training courses held or offered by the Centre	3	4
Workshops or conferences held or offered by the Centre	3	3
PEOPLE AND TRAINING		
New postdoctoral researchers working on Centre research	4	18
New PhD students supervised by Centre researchers	8	27
New Master's students supervised by Centre researchers	0	1
New Honours students supervised by Centre researchers	5	9
New Associate Investigators	3	14
PhD completions	18	15

	2021 TARGETS	2021 ACTUALS
Master's completions	0	3
Honours completions	5	14
Delivery of EQUS mentoring program	1	1
Delivery of EQUS induction program	1	1
COMMUNICATION AND OUTREACH		
Talks open to the public	8	23
Talks, presentations or briefings to government	4	20
Talks, presentations or briefings to industry, business or other end-users	4	20
Training for STEM teachers	60 teachers	0 teachers
Outreach activities for school students	14	17
Industry engagement events	2	2
NEW COLLABORATIONS		
New industry collaborative relationships	1	11
New academic collaborative relationships	1	31
EQUITY AND DIVERSITY		
Female higher-degree research students	20%	25%
Female postdoctoral researchers	15%	7%

Income and expenditure report

	2021 actuals
INCOME	
ARC Centre of Excellence grant	
ARC Centre of Excellence grant	$4,950,089
Administering and Collaborating Organisation contributions	
The University of Queensland	$1,084,734
The University of Sydney	$365,555
Macquarie University	$151,452
Macquarie University, scholarships[1]	
The University of Western Australia	$142,207
The Australian National University	$52,627
Partner Organisation contributions	
Defence Science and Technology Group	$210,000
University of Ulm[2]	$4,724
TOTAL INCOME	**$6,961,388**
EXPENSES	
Salaries	$3,505,796
PhD support	$124,248
Equipment	$546,718
Travel and visitor support	$93,329
Administration, management and other	$102,524
Education, outreach and communications	$125,685
Workshops and conferences	$176,882
TOTAL EXPENSES	**$4,675,182**
ANNUAL SURPLUS	**$2,286,206**

1 As at 31 December 2021, $193,904 is recorded in a separate General Ledger account at Macquarie University. The amount of $193,904 is represented by cash contributions from 2018 to 31 December 2021 (four years).

2 Cash held at University of Ulm and expended against consumables.

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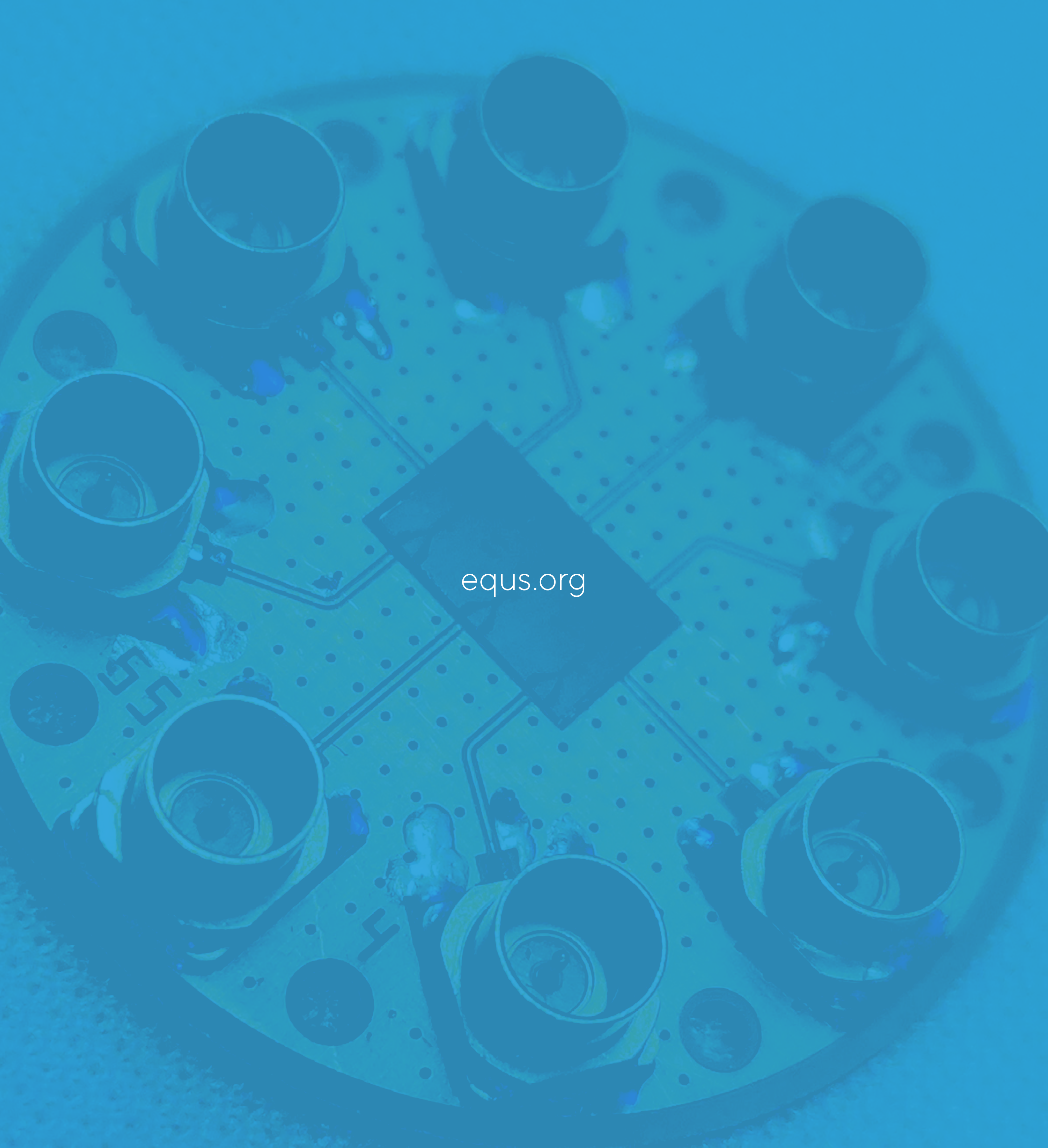

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