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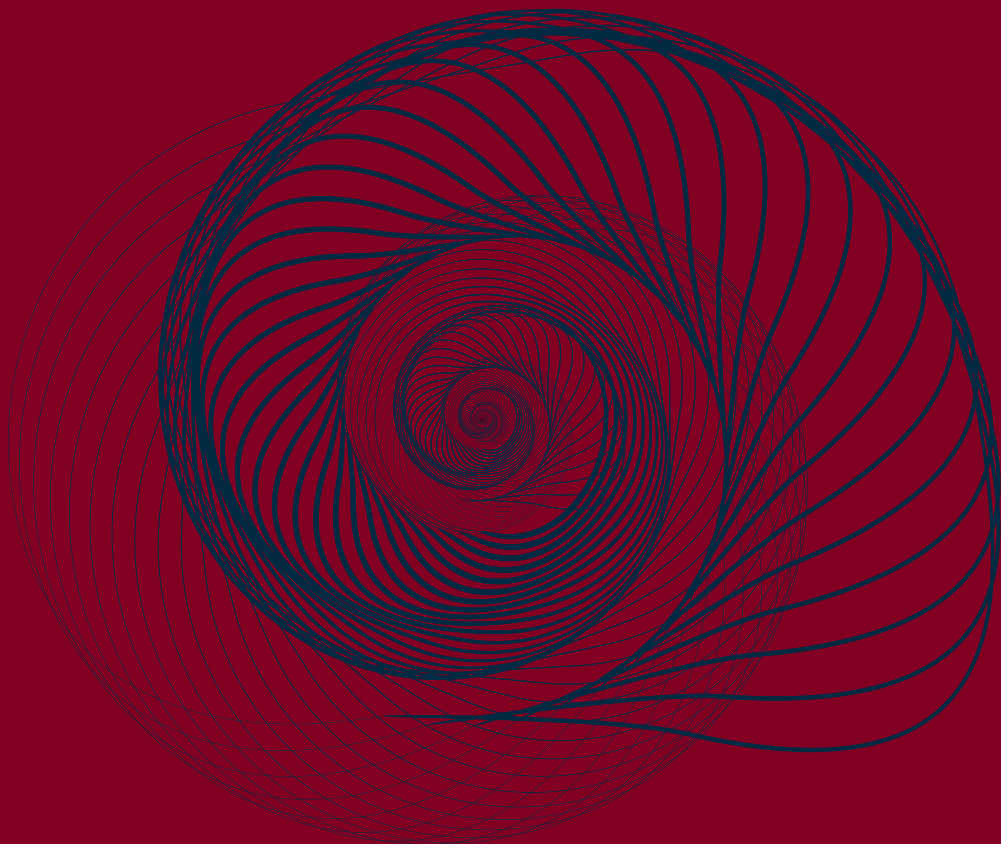

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The Society traces its origin to the *Philosophical Society of Australasia* founded in Sydney in 1821. The Society exists for "*the encouragement of studies and investigations in Science Art Literature and Philosophy*": publishing results of scientific investigations in its *Journal and Proceedings*; conducting monthly meetings; awarding prizes and medals; and by liaising with other learned societies within Australia and internationally. Membership is open to any person whose application is acceptable to the Society. Subscriptions for the Journal are also accepted. The Society welcomes, from members and non-members, manuscripts of research and review articles in all branches of science, art, literature and philosophy for publication in the *Journal & Proceedings*.

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Editorial: The invention of Wi-Fi in Sydney

Robert Marks

Editor

Introduction

I am very glad to announce a paper in this issue that we have labelled as "Great Inventions in NSW 2." It is the account of the invention of Wi-Fi in Sydney by a team at the CSIRO's Division of Radiophysics in the 1990s. I have wanted to include a paper about this invention — now used all over the world in billions of devices, computers, and phones — for some years. This year I came across the transcript of a 2016 interview at the Australian National Museum, obtained permission to publish an edited version of it, and contacted John O'Sullivan, the leader of the team. Wi-Fi was a team invention, and so it is appropriate that Terry Percival, another team member, was also involved in the 2016 interview. The occasion for the interview was the 2016–2017 exhibition in Canberra of "A History of the World in 100 Objects" from the British Museum (see MacGregor, 2012), to which was added the CSIRO's prototype Wi-Fi equipment to be the 101st object in the exhibition. I should also mention that Google Maps, a pervasive phone app, was also invented in Sydney. (See the reference in the Wi-Fi paper.)

The CSIRO team was competing with many overseas computer companies to develop wireless local area networks, and the CSIRO was sued in a Texas court before its intellectual property over Wi-Fi was legally established. The computer companies had apparently been seeking to improve their existing very slow speeds incrementally. The CSIRO team had two advantages: first, their background and experience in radio astronomy (dealing with some of the same issues); and, second, their impressive goal: to allow computers to communicate wirelessly at the much higher speed of at least 100 megabits per second. This and more they achieved. Before the patent expired, their invention earned the CSIRO (and the Australian taxpayer) over $500 million in licensing payments from the computer companies, all of whom adopted Wi-Fi.

Today, it is disheartening to see the Australian government, and the CSIRO, continuing to cut the agency's budget: 350 scientists will lose their jobs, and this is in addition to earlier budget and job cuts under governments of both persuasions. Could a future CSIRO team invent such technology? The prognosis does not look promising.

Other papers in this issue

It is customary for each President of the Society to write a paper for the *Journal* at the end of their term. Immediate past president, Susan Pond FRSN, has written on "Biotechnology: a revolution in progress." As she says, this is a topic that has consumed her professional career. From the serendipitous discovery of penicillin to the discovery of the double helix of DNA[1], recombinant DNA technologies[2], and the AIDS epidemic,

1 On the last day of February 1953, Francis Crick is reputed to have boasted in The Eagle, my old pub in Cambridge, that he and Watson had just discovered the "secret of life."

2 Discussed in 1975 at another old stamping ground of mine: Asilomar, in California.

she recounts her experiences. Susan Pond concludes with the possible future of biotechnology, including the role of AI.

Robert Clancy FRSN and his wife Christine have written a description of a tour sponsored by the Royal Society of NSW, and the State Library of NSW, of Society members and others they led to Europe in the southern spring of 2019, visiting Italy, France, and Britain, as they trod in footsteps of pioneering scientists. Also included is a piece by Robert Clancy entitled, "28 Moments in a history of western science."

Two economists, Steven Hamilton and Richard Holden FRSN, wrote a book (Hamilton and Holden, 2024) that criticised the Australian government's public health responses during the COVID pandemic. There are several chapters that I thought were eminently suitable as papers, and I chose one chapter which describes and critiques the government's actions in procuring vaccines for Australia. I sought and received permission to reprint the chapter as an edited paper. Another chapter critiques the policy on testing individuals for possible infection during an epidemic. The book is well worth reading, as the authors bring their view as economists to the issues of dealing with pandemics. Public health professionals do not possess all the answers to policies to deal with pandemics.

Tim Stephens is a law professor at Sydney who presented a paper at *Ideas@TheHouse* in October 2024, entitled, "The Big Thaw: who governs Antarctica's ice?" Will this discussion about international disagreements in Antarctica prove to be a prediction of future activities in Antarctica?

David Hush FRSN continues his occasional pieces on Mozart. His paper in this issue examines the second movement of Mozart's Piano Sonata No. 2 in F to argue that the number 3 manifests itself on multiple levels in the movement, a phenomenon he labels as Mozart's Secular Trinity.

Sadly, the issue includes two obituaries. Thomas Julius Borody (1950–2025) FRSN is written about by Robert Clancy FRSN. Benno Paul Schoenborn (1936–2025) is remembered by Robert Knott MRSN.

There are 13 abstracts of recent PhD theses at universities in NSW and the ACT. How are these chosen? As the Editor, I approach the universities (usually the Deputy Vice Chancellor Research) to ask for their best theses in the recent past. I do not myself attempt to choose between them; I do however choose the universities to approach for each issue.

An on-line index of the 3,880 papers we have published since 1862

Almost ten years ago, when I was working on making the papers published in the *Journal & Proceedings* since 1867 accessible to us, on-line at the Biodiversity Heritage Library, I hoped that one day a complete index of the pieces would appear.

Has the Society ever published a paper about the poet, John Keats? To answer this question (or any others about papers we have published since 1862), go to the new on-line index, (alphabetical by first author), at https://www.royalsoc.org.au/wp-content/uploads/2025/09/RSNSW_Journal_Index_20250903.html and search by author, title, or date.

For almost all of the papers there is a DOI, a Digital Object Identifier, pointing at a permanent on-line location of the paper. This is an on-line index to all 3,880 papers published by the Royal Society and its antecedents since 1862, in their journals, with their DOIs, which have been supplied by BHL Australia, using the metadata I derived for each paper, at the Journal Archive. We wish to thank BHL Australia for their generosity. The final 156 lines of the index are recent papers (2022–2025) that do not yet have DOIs. We can hope that the BHL can overcome its current funding woes to continue its indexing. The information for each paper includes: Author, Given Names [other authors] (Year) Paper Title, Journal, Volume: Start Page–End Page, DOI/URL.

Using the information (the metadata) in the Journal Archive, BHL Australia has provided DOIs for almost all the papers we have published since 1862, which makes finding any paper very easy. The new index includes these DOIs. The index includes Author's name, other authors (if any), year, title of the paper, journal title, volume number, pagination, and DOI.

Davina Jackson's *RSNSW Bicentennial Bibliography* appeared earlier this year, at https://www.royalsoc.org.au/wp-content/uploads/2025/03/RSNSW_Bicentenary_Bibliography_20250304.pdf, but it does not include DOIs.

The paper on Keats can be found at its DOI, https://doi.org/10.5962/p.361341.

The printed version of the *Journal*

To those of you who are reading this in your printed copy of the *Journal*: thank you. We continue to print copies and mail them out to both subscribers and institutions with which we have an exchange agreement; we receive copies of their journals and they ours. The journals we receive by exchange are deposited in the Dixson Library at the University of New England, Armidale, NSW, and UNE pays us for them, which helps to defray our costs of printing and postage. Our Editorial Board, the members of whom are listed on the inside front cover, have been strong in their support for our continuing to print copies of the *Journal*, even as some other journals stop printing. The main reason, as I understand it, for their support is the archival value of the printed page. There is no way of knowing about the future availability, reliability, and cost of on-line archives, but printed copies, in libraries, will almost certainly continue to be available. And the annual subscription prices are not excessive: from $76 for Australian members of the RSNSW, to $156 for overseas non-members (which is very much less than other similar journals charge their overseas subscribers). Indeed, if the cost of printing and mailing the *Journal* is not covered by the subscription revenues, then we can always raise the subscription prices.

Housekeeping

As always, I wish to thank Jason Antony MRSN for his assistance in producing this issue. I also thank the Editorial Board for their support, assistance, and suggestions.

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Robert Marks, Editor
Balmain, 28 November 2025

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Biotechnology: a revolution in progress

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Introduction

It is customary for each President of the Royal Society of New South Wales (RSNSW) to write a paper for the Society's journal at the end of their term.[1] My sole instruction from journal editor, Robert Marks, was to "write something of interest on a topic of your choice." I have chosen to write about biotechnology, the field that has consumed my career.

Biotechnology harnesses nature's designs of living organisms to develop technologies and products that improve the health of people and our planet.

Needing to limit the scope of this paper because the field of biotechnology is so vast, I can only offer a few snapshots of biotechnology's transformational impacts through my lens as a physician-scientist since the 1970s.

My career expanded well beyond my initial medical and research qualifications. I have crossed and combined disciplines and sectors and worked at the intersections between them, always with a unifying theme: the importance of science and technology to our future. No wonder I was attracted to join the RSNSW with its thought leaders and innovators from across academia, industry, government, public administration, culture and civil society.

Foundations of modern biotechnology

Biotechnology has its origins in the dawn of civilisation when humans were selecting plants for cultivation, microorganisms to make bread, beer, cheese and wine, and animals for domestication. From the early 1800s until the early twentieth century, many scientists began to reveal the basis for observations made during previous millennia.

Fundamental discoveries include: the nature of cells as the functional unit of living organisms; the existence of a nucleus in human, animal, plant and some other cells; invisible internal units (later called genes) that transfer information from one generation to the next and account for observable traits; chromosomes and their role in inheritance; proteins and enzymes; microorganisms; and the concepts of vaccination and evolution.

Penicillin

Modern biotechnology emerged in the 1940s with the large-scale production of penicillin in yeast. During a recent visit to London in August this year, I visited the Alexander Fleming Laboratory Museum. Tucked away in St Mary's Hospital, the Museum celebrates Fleming's discovery of penicillin on 28 September 1928 when he recognised the antibacterial effect of an accidental contamination by mould on one of his agar plates. Fleming identified the

1 Immediate Past President of the Royal Society of New South Wales.

mould as *Penicillium notatum* and named the antibacterial agent penicillin. He published his results (Fleming, 1929).

I had always known that chance was involved in the discovery but not the entire sequence of serendipitous events. In his biography of Fleming, Gywn Macfarlane describes their almost unbelievable improbability (Macfarlane, 1984).

> First, Fleming inoculates a plate with staphylococci and it happens to become contaminated with a rare, penicillin-producing strain of mould. Second, he happens not to incubate this plate. Third, he leaves it on his bench undisturbed while he is away on holiday. Fourth, the weather during this period is at first cold and then warm. Fifth, Fleming examines the plate, sees nothing interesting and discards it, but, by chance, it escapes immersion in lysol. Sixth, Pryce [one of Fleming's former colleagues] happens to visit Fleming's room, and Fleming decides to show him some of the many plates that had piled up on the bench. Seventh, Fleming happens to pick the discarded penicillin plate out of the tray of lysol (in which it should have been immersed), and on a second inspection sees something interesting.

Despite the serendipity, Fleming is rightfully acclaimed for his prepared mind that recognised the significance of his observation. Fleming, Ernst Boris Chain and Howard Walter Florey were awarded the Nobel Prize in Physiology or Medicine jointly in 1945 for discovering penicillin, isolating the active substance from the mould, and developing methods to produce it at scale for therapeutic use. Penicillin was first used extensively and highly effectively during the WW II North Africa campaign in 1943. Introduced for public use in 1946, it represents one of the greatest medical breakthroughs of the 20th century.

DNA double helix

My second stop in August was London's Science Museum to see first-hand another great scientific breakthrough: the double helix model of DNA (deoxyribonucleic acid) created by Francis Crick and James Watson at Cambridge University. The reconstruction displayed in the museum includes some of the metal plates used in their original model.

By incorporating X-ray crystallography results from King's College London, Watson and Crick determined that the structure of DNA is spiral, consisting of two strands of DNA wound around each other in a double helix. Each strand has a backbone made of alternating sugar (deoxyribose) and phosphate groups. One of four bases — adenine (A), cytosine (C), guanine (G), or thymine (T) — is attached to each sugar. The two strands are connected by chemical bonds between the bases: A bonds with T, and C bonds with G.

In April 1953, *Nature* published a one-page article by Watson and Crick (1953) reporting their results, along with articles by Rosalind Franklin (Franklin and Gosling, 1953) and Maurice Wilkins (Wilkins et al., 1953) who were contemporaries at King's College. The iconic final sentence in Watson and Crick's paper reads: "it has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material." This heralded our modern understanding of the role of DNA in inheritance and direction of protein synthesis via messenger RNA (ribonucleic acid). Watson, Crick and Wilkins were awarded the Nobel Prize in Physiology or Medicine in 1962.

Rosalind Franklin was ineligible to receive the Nobel Prize because she had died four years before the award at the age 37 from ovarian cancer. Brenda Maddox in her biography *Rosalind Franklin: The Dark Lady of DNA* presents a detailed account of Franklin's life and the significance of her science (Maddox, 2002). She writes:

> [b]ut could Watson and Crick have done it without the 'dark lady': Rosalind Franklin, the thirty-two-year-old physical chemist … Her research data, which had reached them by a circuitous route and without her consent, had been crucial to their discovery. Watson's glimpse of one of her X-ray photographs of DNA gave him and Crick the final boost to the summit. From the evidence in her notebooks, it is clear that she would have got there by herself before long.

Other research during the 1950s and 1960s unlocked many more advances in biotechnology. Nobel Prizes in Physiology or Medicine, or Chemistry awarded for discoveries made during these decades track many of these revolutionary discoveries.

Recombinant DNA technologies

In 1972, Paul Berg from Stanford University reported success in splicing a piece of DNA from a bacterial virus into the DNA of a virus that infects monkeys (Jackson et al., 1972). He was awarded one half of the 1980 Nobel Prize in Chemistry for his fundamental work on the biochemistry of nucleic acids and recombinant DNAs.

In passing, I note that the other half of the 1980 Nobel Prize in Chemistry was awarded jointly to Walter Gilbert and Frederick Sanger for their contributions to the determination of base sequences in nucleic acids. An initial sequence covering about 90% of the human genome (but missing complex repeated sequences) was published in 2001 (IHGSC, 2001) and the complete sequence in 2022 (Nurk et al., 2022). The capacity to sequence nucleic acids (now very cheaply) marked a turning point in the history of medicine towards preventive healthcare and precision medicine. For example, rapid gene sequencing played a pivotal role in the global responses to the devastating COVID-19 pandemic, enabling rapid identification of and testing for the virus and its variants and development of effective vaccines.

Recombinant DNA (rDNA) technologies involve joining (recombining) pieces of DNA in a test tube, creating identical copies (cloning) in a bacterium or another organism, and expressing the DNA as a protein or ribonucleic acid (RNA) molecule. Key to this process is the ability, using enzymes (restriction enzymes, usually from bacteria), to cut DNA at a specific point (restriction site) in its sequence, produce a well-defined fragment, and then to paste it using ligating enzymes (ligases) into a specific sequence in the DNA of another organism.

When I took up my appointment in medicine and clinical pharmacology at the University of California San Francisco (UCSF) in 1977, I had a bird's eye view of the early days of the Genentech (*Gen*etic *En*gineering *Tech*nologies). This, the world's first biotechnology company and still an icon of the industry, was established in 1976 by venture capitalist Robert Swanson and Herbert Boyer (USCF) with the radical goal of using rDNA technology to produce human proteins at scale.

Earlier, in 1974, Boyer and his colleague Stanley Cohen from Stanford University had filed the first of their patents on the process and products of rDNA. They had succeeded in incorporating human genes into bacteria, thus allowing them to replicate and express the human gene as recombinant protein. Boyer and Cohen used plasmids — tiny rings of DNA that can reproduce in the cytoplasm of bacterial cells — to transport the DNA fragments into bacteria, and a restriction enzyme (EcoRI) that cut DNA predictably at a specific position and produce "sticky ends" that make it easy to paste in a second DNA fragment. They demonstrated that the engineered plasmids reproduced in bacterial cells and thus cloned the inserted foreign DNA. Plasmids were being studied for their role in the growing problem of bacterial resistance to antibiotics.

During their lifetime, the Cohen-Boyer patents, which expired in December 1997, were licensed to Genentech and hundreds of other companies and earned millions of dollars in royalties for Stanford and UCSF.

Science historian Sally Smith Hughes tells the story of Genentech's turbulent, triumphant ride (Hughes, 2009). She writes:

> Genentech's future rested on technological innovation, business acumen, human dedication, and a freewheeling, can-do culture strikingly different from anything the pharmaceutical industry offered. Its handful of irreverent scientists captured a swiftly expanding audience as they cloned and expressed three medically significant genes in three successive years: human insulin, human growth hormone, and human interferon.

In 1978, Eli Lilly licensed Genentech's rDNA technology to produce insulin. In 1982 the US Food and Drug Administration (FDA) approved the Genentech-Lilly recombinant human insulin (Humulin), the first rDNA product to reach the market. The production of pharmaceutical grade human insulin at scale represents one of the most significant accomplishments of modern medicine.

In 1985, Genentech received FDA approval to market its own product: human growth hormone for children with growth hormone deficiency. This was a major step forward for patients previously receiving the hormone pooled from multiple cadavers and thus at risk of developing Creutzfeldt-Jakob disease from any donor carrying the neuropathogenic protein known as a prion.[2]

Development of products based on the rDNA revolution necessitated a revolution within regulatory agencies, such as the FDA and Australia's Therapeutics Goods Administration (TGA). Divergent views about the risks and regulation of rDNA technologies have been debated ever since the meeting held in 1975 at the Asilomar Conference Grounds in California, when a group of scientists agreed on guidelines defining what experiments should and should not be done. They were concerned, for example, about the potential to create new organisms that could infect laboratory staff and the wider public. Such discussions continue today (Cobb, 2025).

When I returned to Australia in 1985, I was very much involved in these debates through my service as an independent member of many TGA Advisory Committees. Many of the initial concerns raised

2 Deaths had occurred. [Ed.]

at the Asilomar conference of 1975 never materialised. It was always a good day when, based on thorough risk-benefit analysis, we could recommend approval of the next therapeutic advance created using rDNA technologies. They continue to produce breakthrough treatments. Recent approvals by the TGA include potentially curative antibodies for metastatic cancers, including melanoma, and antibodies that appear to slow progression of Alzheimer's disease in patients in the early stages.

The AIDS epidemic

From 1980–1984 I was amongst the group of physicians at the San Francisco General Hospital (SFGH) treating patients with a new disease initially known as "gay-related immune deficiency" (GRID). In 1981, the US Centre for Disease Control (CDC) reported similar cases in New York and Los Angeles. Previously healthy young men were presenting with rare infections such as *Pneumocystis carinii Pneumonia* (PCP) and atypical tuberculosis. Some developed tumours such as Kaposi's sarcoma, a rare and aggressive cancer, and lymphomas. Many manifested unusual allergies to their medications.

The CDC used the name "acquired immunodeficiency syndrome" (AIDS) for the first time in 1982, providing as the case definition, "a disease, at least moderately predictive of a defect in cell-mediated immunity, occurring in persons with no known cause for diminished resistance to that disease." It had also become apparent that several groups of people were at risk of AIDS. Amongst them were blood transfusion recipients, injecting drug users, and babies born to mothers with AIDS.

AIDS was proving to be a death sentence, sometimes within weeks of diagnosis. The intensive-care wards at SFGH were full of AIDS patients. By 1983, the disease had affected and killed hundreds of patients in San Francisco alone. SFGH established specific wards in collaboration with the gay community — Ward 86 for outpatients and 5B for inpatients — to ensure optimal care.

AIDS was also becoming recognised as a global epidemic as reports streamed in from many other countries, including Africa where transmission was largely in heterosexual populations.

In 1984, an RNA virus, later named Human Immunodeficiency Virus (HIV), was identified as the infectious agent (Gallo et al., 1984; Barré-Sinoussi et al., 1983). Then followed four decades of research and development resulting in tests to identify patients, screen blood supplies, sequence the wide variety of viral variants, unravel the life cycle of the virus (including the many years between initial infection and clinical presentation), and introduce safe and effective anti-HIV drugs.

The first patients with AIDS in Australia were diagnosed in Sydney and Melbourne in 1982 and 1983. Australia mounted a strong, proactive and effective medical and community response to the epidemic. Key leaders included: RSNSW Fellows David Cooper and Chris Puplick; Distinguished Fellows Marie Bashir, Peter Baume, Barry Jones and Michael Kirby; as well as Neal Blewett, William Bowtell, Julian Gold and Ronald Penny. There were many more.

A Liberal NSW Senator from 1974–1990, Peter Baume held several ministerial and shadow portfolios and was member of the AIDS Parliamentary Liaison Group from 1985. In 1991, he delivered a comprehensive report on the inquiry he conducted into perceived dissatisfaction, particularly by the AIDS community, with the timely availability of anti-HIV agents in Australia (Baume, 1991).

By that time, I had been back in Australia for six years as Professor of Medicine and Clinical Pharmacology at the University of Queensland and served on several TGA committees. In 1992, I was invited to join the "new" Australian Drug Evaluation Committee (ADEC; now known as the Advisory Committee on Prescription Medicines) established as part of the Baume recommendations. I served as Chair from 1994–1996.

During these years, we approved several breakthrough anti-HIV agents, including HIV protease and non-nucleoside reverse transcriptase inhibitors. These and many other advances led to the registration of dozens of small-molecule anti-HIV therapies, including the modern long-acting injectable drugs that provide durable suppression of HIV and enable patients to live a normal life.

Despite these successes, there remains no effective anti-HIV vaccine. The many strategies designed and tested have been foiled by complexities of the virus, including its high genetic diversity and its interactions with the host, such as integrating into cellular DNA thus becoming "hidden" from any immunologic response.

In 1997, I entered the second phase of my career, joining Johnson & Johnson Research (JJR), an Australian-based subsidiary of Johnson & Johnson Inc (J&J) established to design and build RNA or DNA molecules that can target and cut specific nucleic acid sequences. JJR had licensed the patents on the discovery of naturally occurring RNA enzymes (ribozymes) in plants from the CSIRO spin-out Gene Shears Pty Ltd to investigate their therapeutic applications in humans.

One of JJR's projects was to develop a once-only treatment for patients infected with HIV that reduces viral load, preserves the immune system, and avoids a lifetime of antiretroviral therapy: the equivalent of a vaccine. We harvested bone marrow stem cells from patients, introduced the anti-HIV ribozyme gene using recombinant technology, then returned the modified stem cells to the patient to engraft, divide, and differentiate into a pool of mature immune cells that would be protected from HIV infection, in theory.

We designed and conducted the first ever randomised, placebo-controlled Phase II trial of this cell and gene therapy by recruiting 75 patients infected with HIV in Sydney, at Stanford University and the University of California Los Angeles. The trial was conducted under the regulatory auspices of the TGA in Australia and the FDA in the USA. David Cooper was the principal investigator at our clinical trial site in Sydney. Leaders at JJR included Louise Evans (medical), Janet Macpherson (cell and gene manufacturing), and Geoffrey Symonds (scientific). We filed many patents along the way and published the results in *Nature Medicine*, reporting that our cell and gene therapy approach was safe but did not achieve a sufficient population of protected cells to reduce viral load (Mitsuyasu et al., 2009). Nonetheless, it was a promising start.

When JJR closed in 2009, we formed two companies. The molecular diagnostics technologies that had been invented to underpin the clinical trial were spun out by Alison Todd and Elisa Mokany into the venture-capital-backed company, SpeeDx. It continues today as a successful company at the Australian Technology Park. Calimmune Australia was formed as a division of the US parent, Calimmune, to continue work on the stem cell gene therapy platform. The entire company was acquired by CSL Behring in 2017 to complement its gene and stem-cell based therapies portfolio.[3]

As for me, increasingly concerned about the well-being of our planet, I took up a position in industrial biotechnology in the newly established Dow Sustainability Program at the United States Studies Centre (USSC) at the University of Sydney. There I developed and led the Alternative Transport Fuels Initiative. From its inception, this program was framed as a national and international collaboration between the wide variety of partners required to improve the environmental performance of all transport modes, but especially aviation.

Aviation must join the global transition to low-carbon emissions but has fewer options than road transport, given its dependence on jet fuel from fossil oil, which is high-energy-dense, light, low-freezing-point, relatively inexpensive, and safe. Sustainable aviation fuels with similar properties to conventional jet fuels can be produced using industrial biotechnology processes, but the challenge is to reach scale (Pond, 2017).

I will leave this story here to be told another day, except to note the recent commitment by the Australian Government of $1.1 billion to support the production of low-carbon liquid fuels in Australia for industries such as aviation, heavy freight and mining.[4]

The future of biotechnology

By covering but a tiny sliver of the field, I hope nonetheless to have given an inkling of the power of biotechnology to enhance our understanding of nature and deploy it for the benefit of ourselves and our biosphere.

The biotechnology revolution will accelerate exponentially, given present-day capacities to read (sequence), write (synthesise), and edit (add, remove or change a single base) DNA, and converge the biological with other rapidly advancing technologies, such as artificial intelligence,[5] information technologies, materials science and engineering, nanotechnology, quantum computing, and robotics.

Risks and unanticipated consequences always stem from new technologies. We must remain vigilant to any new threats that they pose to public health, individual safety and national security. The RSNSW will continue to lead multidisciplinary debate and engage the wider public with the aim of driving the brightest possible future for humanity.

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3 https://investors.csl.com/PDF/f00cb92f-cb30-4ed5-a5db-40a2c960f233/CSLBehringAcquiresUSBiotechCompanyCalimmune

4 https://www.dcceew.gov.au/about/news/new-prod-incentive-low-carbon-liquid-fuels

5 The 2024 Nobel Prize for Chemistry was awarded partly for the development of an AI model to solve a 50-year-old problem: predicting proteins' complex structures. [Ed.]

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Wires, wi-fi and the future

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Interviewed by Robert Bunzli at the Australian National Museum, Canberra, on 9 December 2016.[1]

Introduction

In 2016, John O'Sullivan and Terry Percival were granted the World IT Service Association's Eminent Persons award. They are only the fifth and sixth people to receive this award. In 2017 John O'Sullivan, Terence Percival, and David Skellern were awarded the IEEE Masaru Ibuka Consumer Electronics Award for pioneering contributions to high-speed wireless LAN technology.[2] John O'Sullivan was awarded the 2021 Japanese Okawa Prize.[3]

Welcome

Robert Bunzli: Hello, and welcome to the National Museum of Australia, Canberra. Welcome to our event "Wi-fi, wires and ways to the future." My name is Robert Bunzli. I'd like to begin by acknowledging the traditional owners of the land on which we meet, the Ngunnawal and Ngambri people, and pay respects to their elders both past and present, and to their future leaders coming through.

I'd like to introduce our very special guests for this conversation. May I introduce Dr Terry Percival? Terry has more than 30 years' experience in delivering ICT research outcomes, specialising in radio communications and applications for high-speed networks. Previously, he was a laboratory director of NICTA (National ICT Australia), and chief research scientist at CSIRO's (Commonwealth and Scientific Industrial Research Organisation) telecommunications division. While working at NICTA, he guided the creation of 10 successful spin-out companies and the transfer of research outcomes into government and industry.

As co-inventor of technologies for wireless communications, he led the creation and patenting of technologies that underpin wi-fi. As a result, more than $500 million in royalties has flowed to CSIRO. He's received numerous national and international awards, including the 2009 CSIRO Chairman's Medal with the team, and the European Inventors Award, He was made a member of the Order of Australia in 2014.[4]

1 This is a transcript, courtesy of the National Museum of Australia, edited by Robert Marks (with others' help) from an audio recording made at the National Museum of Australia, Canberra. The editor thanks John O'Sullivan for amending information about the team and its efforts, and Dov Rosenfeld for his elucidation. Audio is at https://www.nma.gov.au/__data/assets/audio_file/0010/529552/wires-wi-fi-and-the-future-091216.mp3

2 See https://2017.ieee-iscas.org/2017-ieee-masaru-ibuka-consumer-electronics-award.html [Ed.]

3 See http://www.okawa-foundation.or.jp/en/activities/prize/data/2021_e0.pdf [Ed.]

4 See also a lunchtime interview with Terry Percival at the Australian Museum in 2019, at https://australian.museum/blog/at-the-museum/lunchtime-lecture-terry-percival/ and also https://www.epo.org/en/news-events/european-inventor-award/meet-the-finalists/john-o-sullivan-graham-daniels-terence [Ed.]

May I also welcome Dr John O'Sullivan? John has had an extensive career in wireless signal processing and radio physics in both research and commercial contexts. He worked with the Netherlands Foundation for Radio Astronomy, leading the engineering team for the Westerbork telescope. At CSIRO, he led a research group in signal processing and later in wireless communications, which resulted in key technologies underpinning wi-fi used in 15 billion devices worldwide, as of December 2016.

He led a team which developed a single chip, a fast Fourier transform processor, which has found applications in military surveillance and astronomical applications. He returned to radio astronomy with CSIRO on the Australian Pathfinder, or ASKAP project, for the International Square Kilometre Array radio telescope. He's a winner of the Prime Minister's Prize for Science 2009,[5] the European Inventors award, two CSIRO Chairman's Medals, the 1992 CSIRO medal for the development of fast Fourier transform technology.

Welcome, gentlemen. Those are extremely impressive CVs. It's wonderful to have you here at the National Museum for this conversation, mainly on the development of wi-fi, but also later on, touching on where you see technology and wi-fi leading us into the future.

For the 2016–2017 exhibition, "A History of the World in 100 Objects" from the British Museum, the National Museum chose your prototype equipment to be the 101st object in the exhibition. This is the National Museum's contribution to the exhibition, and your equipment is part of the National Historical Collection.

Could you reflect on how you felt when you heard that your prototype equipment was selected as one of these key cultural objects in the history of humanity?

Terry Percival: Yes. I think I was a bit shocked when we got the phone call, the message they wanted to put it on display, and then I looked at the 100 objects that were already there. I did realise that one of the interesting objects, and an interesting choice, is a credit card. It's very boring to display a credit card in a museum, but that's because we've all got them in our pocket. It turns out, the other thing we've all got in our pocket is wi-fi. I suddenly said, "Oh, it's not a silly idea at all, it's actually, it is something that's changed the way … "

RB: It's transformative.

TP: Yes.

RB: There's probably 100 devices in this room right now.

TP: All competing with each other.

RB: Yes. Giving our wi-fi a bit of a beating.

TP: Yes. John?

John O'Sullivan: I guess it's a particular honour when you see the sorts of objects that precede us there, and always mindful of the fact that I am continually surprised at how smart people were in ancient times. There are some staggering things.

RB: The quality of some of the craftsmanship on those artworks from the time that they were made is really incredible, isn't it?

JO'S: The time spent on them. Maybe that's something we can't do anymore, we don't have time, because of things like wi-fi.

RB: Because we're all looking at our phones. You two are credited as co-inventors of wi-fi.

5 See https://www.scienceinpublic.com.au/media-releases/2009-science [Ed.]

I'm just wondering if you might be able to take us through how this project started and how you two came together or were you working in separate teams and working in parallel? Just give us a bit of a brief overview of those early days.

The beginnings

TP: I'll jump in. It's all John's fault, of course. We actually did our PhDs at the same university[6] on the same radio telescope project, although John had left by the time I started. Then we came together.

JO'S: Nothing personal.

TP: Yes. Then we met up at the CSIRO when the CSIRO was building the Australia telescope at Narrabri. By then, we'd often work somewhere else. I got a phone call from John in 1991, that I'll never forget. I was painting my living room — I took a week off to paint the living room — and I got this phone call, "Do you want to come to lunch?" I said, "Yes, better than painting." I went out and had lunch with John and some of the other friends, and he said, "I've got this exciting new project coming up. We're going to build the world's fastest wireless LAN [local area network]."

My first question was, "What's a wireless LAN and why would you want one?" Back at the office,[7] John showed me his laptop — I'd never seen a laptop before. I think I was vaguely aware of it, but I'd never actually used one, and John had one. Maybe John, you want to say — what frustrations you had with it, I think you —

JO'S: Yes. I think it goes back to around about 1990, a couple of years before that even. I was challenged by my boss at the time, Dr Bob Frater: "We need to make an impact. Would you like" — speaking to some of us — "to turn your skills built up in radio astronomy to more commercially oriented research?" "We need to make an impact" is Bob's favourite term.

RB: Turning that "blue sky" research into applications?

JO'S: Exactly. At that time, as Terry points out, laptops were starting to make their presence felt in business environments, access to a computer to take notes, things like that. In a research environment in particular, something called "networks" was beginning to make an impact. The network at the time — the ethernet — was a pretty clumsy thing, it was a cable of about a centimetre in diameter that had to run all the way through the building and you would actually physically tap into it with a little screw attachment. That was the way you would connect to the ethernet.

After discussions with Denis Redfern in particular and a number of CSIRO leaders, I initiated and led the team looking at wireless networks. We then got significant extra funding from CSIRO and created a new group to look at wireless networks and the telecommunications "last mile" problem. This enabled the new appointment of key players including Terry Percival and Graham Daniels. I later asked Terry to take over direct leadership of the wireless network effort which he did with distinction.

To cut a long story short, we started to think, "Well, what if wireless networks existed? What if you could do a wireless network that ran at the same speed as the best wired networks? Then you could

6 University of Sydney. [Ed.]

7 At the Radiophysics Division of the CSIRO, Marsfield, Sydney. [Ed.]

have all these advantages of the networks, access to people, lots of data, email, stuff like that." This was before the World Wide Web[8] though, before browsers. It was a bit of a leap of faith. Everybody that came on board bought into it.

Shooting for the stars: 100 megabits/sec

RB: You were proposing 100 megabits per second speed as something that might be achievable, which is pretty incredible given that even today, as we are wiring up the NBN [National Broadband Network], we're looking at wired connections that are may be 25, 30 megabits per second. You were really thinking big.

JO'S: Yes. We had various ideas of how this might be used. We saw things like training videos, somebody working, a mechanic working in the bowels of an aircraft, people in lecture theatres being able to access information about the lecture. I think like so many of these things, you only see a piece of the picture — particularly, so many inventions were based on work type usage, but within the shortest possible time. It turns out the killer app is in fact entertainment. What we see now is social networks —

RB: Build it and they will come.

JO'S: Yes.

RB: I heard that you'd been working on trying to find exploding black holes, and I'm wondering if some of that work led to the way you were thinking.

JO'S: Certainly. In a way, there are a number of things. I think all of us in the team — and this was a team[9] — none of us could've done it on our own, I believe. That was an important aspect. The reason the team was a good team was because we'd all cut our teeth working on different challenging problems. One of them for me was a failed experiment. In fact, a series of failed experiments that got ever more complex, looking for exploding mini black holes, these microscopic black holes that Stephen Hawking proposed might be left over from the original Big Bang.

RB: That blows your mind, doesn't it?

JO'S: Yes. If you were near one of these things when it went off, it would've blown your mind. We thought, maybe if they are there and Stephen Hawking was suggesting that the smaller the black hole, the faster it would radiate energy — and it would maybe explode. Martin Rees, the Astronomer Royal, suggested that it would be like an electromagnetic pulse. You might actually be able to see this over astronomical distances. We set out to try and find it.[10]

RB: Terry, I was watching an episode of "Catalyst" (on ABC TV[11]) about this, and I took particular note because I heard you talking about these early days, and you had a little comment about the Star Trek communicators. It made me think how some of

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8 See Grant (2024) [Ed.]

9 The CSIRO team was John O'Sullivan, Terry Percival, John Deane, Graham Daniels, and Diethelm Ostry. See https://www.epo.org/en/news-events/european-inventor-award/meet-the-finalists/john-o-sullivan-graham-daniels-terence [Ed.]

10 To correct for distortions and to increase the search efficiency, O'Sullivan invented a Fast Fourier Transform (FFT) computer chip, which enabled Orthogonal Frequency Division Multiplexing: many channels of information combined into a single fixed bandwidth channel — the basis of wi-fi [Ed.]

11 "Wifi windfall," ABC TV Catalyst, 8 Oct 2009, Season 10, No. 29. https://thetvdb.com/series/catalyst/episodes/4136351 [Ed.]

these popular science fiction shows sometimes actually lead the way, predict the way to the future, and they get people who are at that stage of development to think about applications that maybe they wouldn't have thought about.

TP: Yes. I think that's true. Science fiction writers are an interesting source of imagination and technology prediction. Someone pointed out that in Kubrick's "2001: A Space Odyssey" one of the astronauts was actually using something that looks remarkably like an iPad. That film was made in 1968. There are those predictions out there, if you look at it. You've got to use that imagination, and the Star Trek communicator obviously is what we've got in our pockets today.

RB: Yes. Looks just like our phone, really. Only not as powerful as our phones.

TP: That's right. Our phones do a lot more now.

The keys to the CSIRO invention

RB: Yes. Maybe you could just tell us — this is a rather broad question — what was it that your team did that was so great? I believe there were 20, 22 different research teams around the world working towards some sort of wireless solution to these networking problems. How was it that your team beat them all to the gun?

JO'S: I think we've probably both got a take on this.

TP: We went through thinking from the original ideas with various stages of progression that we come up with paper and whiteboards. People still use whiteboards, which is good — not blackboards. We did that, and I think the fact that the target was 100 megabits per second, the device that's on display, put in the Museum now, actually will run at 150 megabits per second. We really wanted to push it.

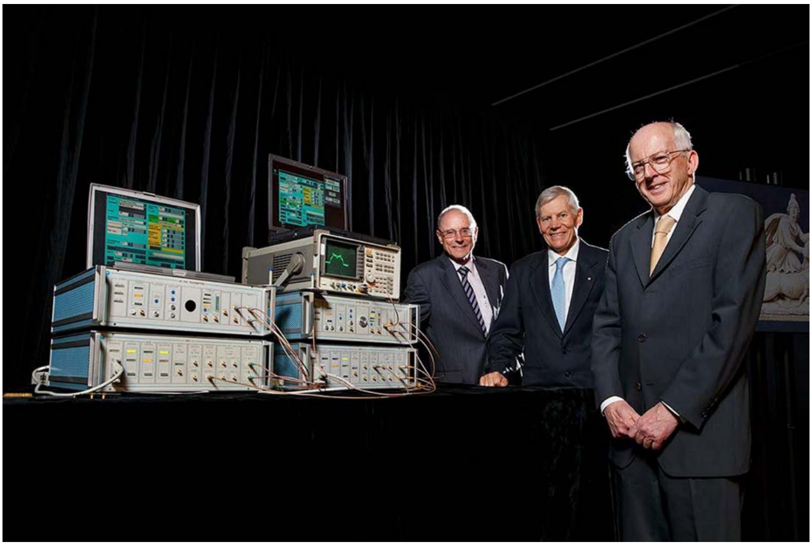
We weren't afraid of pushing the frontiers of technology and using the skills that we'd developed in the various radio-astronomy projects. We knew we could build complicated devices. There's actually been a significant study done on the other 22 teams around the world as part of our legal proceedings that we've gone through, which we'll come to later. They showed they were all trying to get just 10 megabits per second or 20, and they were struggling to get that far. They were building on existing networks, and just doing incremental changes, whereas John, we said "just scrap all that and try and find something that's really going to go fast."

JO'S: Yes. I'd second that. I think the 100 megabits per second was, I don't know, maybe I'd like to call it inspired, but it might've been lucky.

RB: Foolish?

JO'S: Lucky or a foolish choice because that was the thing that meant we couldn't rest on our laurels. We had to come up with something quite new. It's all about "reverberation," radio reverberation.[12] Once you get beyond a megabit or something like that, you really have to do something to solve reverberation. I think with the small team, with diverse skills ranging from maths to physics to engineering, software, we argued with each other in rooms and in front of whiteboards and in corridors. Gradually, you'd say, "Oh, wait a minute." Somebody

12 Reverberation occurs where radio waves bounce around the surrounding environment causing an echo that distorts the signal; "each bit would be roughly three metres long and typical echoes could traverse many times that length!" — O'Sullivan (2018) [Ed.]



John O'Sullivan, Terry Percival, Graham Daniels and the WLAN test bed (NMA)

would ask, "what if we did this?" and that would provide part of the solution and then that would uncover the next set of problems.

RB: What were the key problems to overcome?

JO'S: From my perspective, one of the important ones was the idea that if you try to send the bits one after another, then you run into this reverberation problem full on. The first step was "what if we split the bits and send them together, but on different tones" or frequency channels. Then one of us realised that actually, we had the technology to do that.[13] That's what a transform does.

There was a sequence of steps like that. Terry, you'd probably see a different set of things.

TP: Yes. I think that was one of the things. Reverberation in the room. And the fact that you wanted 100 megabits means you had to do something totally different. We had to apply error correction. There's also the classic fading problem that you get with your mobile phone. Sometimes you walk around the corner, it doesn't work. We had to overcome those sorts of problems, because that was part of it.

I think the solution we came up with in the end is now actually starting to form the basis of 4G and 5G telephone networks. The solution we'd come up with is now scaled. It's the only way to make wireless networks go fast.

And what was the reaction from the computer companies?

TP: We started out with the first prototype,[14] which is these boxes this big. Then we went around the world. John and I separately went around the world to various large computer companies, which we'd better not

13 See Bracewell (1965) and Hamaker, O'Sullivan, Noordam (1977) [Ed.]

14 See photos of the early prototypes at https://www.nma.gov.au/explore/collection/highlights/wi-fi-prototype [Ed.]

name. They said to us, "No, no-one wants to go 100 megabits." One person who was actually on our side even said, "Two megabits is the most you'll ever get out of the back of a laptop." Another person said, "Wireless is a passing fad. That's just one of those new fads."

JO'S: In fairness, we did come across one researcher in IBM research whose eyes were big as saucers as soon as we talked about this.

TP: That was a meeting at IBM's Thomas J. Watson Research Center. I think John gave the story, he scared me with it, he went there first, he said he walked in the corridor and there on the board are photographs of all their Nobel prize winners.

JO'S: As you drive up, there's this building covering the entire mountainside.

TP: That was IBM research. They love it.

JO'S: They had a budget cut bigger than the entire CSIRO budget.

RB: It must've been a bit intimidating, I suspect.

TP: He was, but he was a champion. He helped us. But IBM decided to get out of the networking game, basically, and they got out of the laptop game in the end. That didn't go anywhere. It was ironic that the one person who wanted to work with us worked for the company that decided to pull out.

RB: Goodness. It's a lot about the echoes and the waves. I imagine if you looked around this room, we can't see them, but there's just radio waves going everywhere on various frequencies. It's making sense of that, and isolating those frequencies and putting the package back together.

TP: And where is interference coming from? All those problems we had to overcome. This made the solution quite complex. Even later on, people are saying "That's too complex, it's going to be too big an integrated circuit, it's going to be too power-hungry. It's just not feasible." That's a good example, that's why we built it. We had to build a chip to convince people that it would work, and that's one of the later chips we built. There's a photo of John and me holding up the first product that came out of this work.

RB: Yes. What was that moment when you were able to say, "Okay, we have prototyped it, we can take this now and run with it"? Was there a signal that inspired you to say, "Okay, we're set to go to sell this"?

TP: Yes, I think there was. We were wheeling this box around and we tried a large number of different parameters. The advantage of that first prototype is we could make it do anything. We could control all the different parameters, hundreds of different combinations. We found one that worked, that gave us the sense to go on and go around the world talking to people. It wasn't until we actually built one that was a reasonable size and we had them sitting in the lab, and it kept giving zero errors no matter what we did. That was the moment, in 1997, when we had that going, we knew that it works, we could prove it, we could do anything. It's going to work.

RB: Zero errors?

TP: Zero point zero zero errors.

JO'S: I'm going to say, from my perspective, I remember a series of eureka moments as we as a team would see the answer to some part of the problem, and you'd think, "Wow, we've got something here." Then you go to a prototype. There were further important things for me.

There was a company, Radiata.[15] Terry was one of the co-founders, a company started by Neil Weste and Terry and David Skellern, who were collaborating with us. That company demonstrated the first chips. These are chips this size, that were demonstrated at Net World Plus Interop in Atlanta the week before the Sydney Olympics. They were the first chips to meet the new wi-fi standard.

RB: Right. Wi-fi. Did you guys come up with the term "wi-fi"?

JO'S: No. We engineers came up with the "802.11a standard". The marketing folk took one look at that and said, "That will never fly."[16]

RB: Okay. That makes sense. I've been working on a project here at the Museum with these robots that we send around and we give virtual tours of the Museum. As part of that project, we had to upgrade the wi-fi, and I had to get deep into it. Those numbers and that terminology really does spin my head. It's not really my thing. I suspect a lot of people in the audience get lost in some of the technicalities of it, but it doesn't matter because we just have to hit "connect to the local hotspot." That's all we need.

JO'S: We're standing on the shoulders of lots — lots of people who put together complex standards. It's incredible how much complexity is hidden from us all now.

Patents and lawsuits

RB: Yes. Just speaking of complexity, you then moved on, I'm sure there were other stages, but you then moved into this titanic battle with the technology companies around the world. CSIRO launched a test legal case against one company, Buffalo Technology, and then everyone just countersued you at the same time. Do you want to make some reflections on that time? You'd done the research and the work, and then now suddenly, this thing landed on you. That must've been a bit overwhelming.

TP: Yes. We need to backtrack and point out that we did lodge a provisional patent[17] in 1992 and then we lodged a final patent specification in 1993, saying that if you want to build a high-speed wireless local-area network, then this is the way to do it. Detailed drawings, the works, masses of legal phraseology about modulation means and plurality of devices, all those terms lawyers love. This patent was granted in the US on January 23, 1995. So that was fine.

As John said, in 2000, we showed chips that met the new standard the IEEE (Institute of Electrical and Electronics Engineers) had just agreed to, with a lot of input from us, that this was the way to do it.

Then people started to ship products. We had a patent that was on those products.

RB: Once your technology was in the IEEE standards, that's when it just started being used without payment?

15 Radiata was founded by David Skellern and Neil Weste from Macquarie University, along with Terry Percival. Radiata demonstrated the first working Wi-Fi system based on the IEEE 802.11a 5-GHz standard, and, in 2000, Radiata was the first to use the 802.11a standard on chips connected to a Wi-Fi network. Radiata was acquired by Cisco later in 2000 for USD 295 million. [Ed.]

16 The name Wi-Fi was coined by the brand-consulting firm Interbrand, which also created the Wi-Fi logo. See https://en.wikipedia.org/wiki/Wi-Fi [Ed.].

17 See NAA (nd) and https://www.naa.gov.au/sites/default/files/2023-12/NAA-202081854-WLAN-patent.pdf [Ed.]

TP: Yes. I might add that, before the IEEE issued that standard, they looked through patents and we informed them that we had a patent, and we explained it to them. On their website, they say these are the patents we know about which you may or may not choose to go and licence. Our patent was the only one at that time based on that standard. But we'd told the world about the patent, and no one was paying us royalties. So it's time to do something about it.

RB: Yes. But you wouldn't have known what you were letting yourself in for.

TP: No, I don't think so.

RB: Do you want to take us through that?

TP: I was a naïve engineer. I thought if you'd go knock on the door: "Here's a 20-page patent, your product is using it, let's negotiate." Basically, you get: "You're from Australia," you don't get a response.

JO'S: I think the CSIRO board are to be congratulated for hanging in there, because it's been a long process. Terry's been involved in it right through.

TP: It started in 2003, with trips around America, with CSIRO legal people going around visiting the companies, engaging lawyers, writing letters. Then it went to trial, with one company, Buffalo Technology, which picked itself. Basically, it refused even to negotiate. All the other companies engaged in stalling tactics. We took them to court, we went for the court process. There was a judgement made, which they appealed, and then suddenly, eight large companies — and by large, we mean the big boys…

RB: Apple, IBM?

TP: … IBM, Intel, Microsoft — counter-sued CSIRO. Suddenly, they put a lawsuit on the CSIRO in California, although our original case was in Texas. California, because they like doing things in California, and they wanted to sue us and prove our patent invalid. We went to California and said, "We've already done a case in Texas, so it should all go to Texas," which it did.[18] Then suddenly, we ended up in the mother of all lawsuits in Texas with nine companies being sued by CSIRO.

All the inventors — John, myself, John Deane, Graham Daniels, Diet Ostry — and a number of other people were deposed by their lawyers. Either we went over to the US several times and sat down in a room for days while they grilled us with questions, or they sent some of their lawyers out here to grill other people.

Settlements

TP: Then it ended up, finally, after delays. If anyone's going to pay you $50 million, they don't want to pay it tomorrow — though, if they can pay it next year or the year after or the year after, they'll delay it. We ended up in court — in fact, various shenanigans went on and they ended up paying before the final verdict came through. They all paid up.[19]

RB: They caved.

TP: They all caved. It was quite funny: on the first day in the court case, there were ten lawyers there. The next day in the court case, there were eight, because two of their client firms had already paid up and gone home.

18 CSIRO wins transfer of US WLAN court case https://phys.org/news/2006-12-csiro-wlan-court-case.html [Ed.]

19 Australian WiFi inventors win US legal battle https://phys.org/news/2012-04-australian-wifi-inventors-legal.html [Ed.]

JO'S: I think technically it's called "a settlement."

TP: A settlement, yes.

RB: An agreement was reached.

TP: Gentleman's agreement.

RB: You may not be able to say, but which was the last company standing?

TP: There is still an outstanding case with Cisco, which is an argument about — after a lot of shenanigans, they tried to prove the patent was invalid. They tried to prove that what's called "inequitable conduct" by, in fact, me and to a lesser extent John, that we had deliberately deceived the US Patent Office in getting the patent: we had withheld important information. That fell over. They got the patent re-examined twice. This just kept going on.[20]

In the end, all the cases ended up being just about damages, how much money they would actually pay, what the percentage was. Again, it's not just the royalty figure, there were also damages because they didn't pay. There's one case that's going to be finalised in May next year in Texas.

RB: Then you can draw a line under that.

TP: Yes.

Technical developments in the future

RB: Wow. We've got rivers of gold coming into the Australian taxpayers' account from this blue-sky research, this pure research, this radio telescope, radio-astronomy background that you both come from. It's an interesting observation that these days funding from everyone is often decided purely on the basis of something that's going to deliver an immediate return. Do you have observations on how science funding or technology funding from the public purse is handled?

JO'S: I'm certainly a great believer that you need a variety of approaches. I don't think blue-sky research on its own will get you there. A mix of blue-sky and more outcome-oriented research is appropriate. I think we benefited, as much as anything, from the people, as I said before, who'd cut their teeth on some of the difficult problems in blue-sky research and other research. It's the training of the people, probably, that's one of the important things.

The other comment is, if you go ahead to do something — whether it's a small startup, technology startup company, or a big research project — my experience has been, you can only plan so far, and a short way down the track you're going to get blindsided by something you didn't see, and you'll probably change direction. I think you need to preserve the flexibility to change direction.

TP: And don't give up quickly.

RB: Yes.

TP: There's a lot of nonsense talk at the moment about fast failure. A lot of people tried to fast fail this project. I even had one unforgettable conversation with a bureaucrat who said, "Look, we'll just back down and let the rest of the world catch up, and then we'll see where we're going." You don't do that!

RB: Let the world catch up?

TP: You don't let the world catch up. You don't slow down. If you're ahead, you go

20 See https://law.justia.com/cases/federal/appellate-courts/cafc/15-1066/15-1066-2015-12-03.html and https://www.stout.com/en/insights/article/csiro-v-cisco-clarification-federal-circuit-patent-damages-issues and finally https://patentlyo.com/media/2016/06/CSIRO-v.-Cisco-Petition-for Certiorari.pdf [Ed.]

faster. Australians love sporting analogies; this is a favourite of mine. A question for the room is, who knows who Lorraine Graham is[21]? Ever heard of her? You all watched her for 45 seconds in September 2000, chasing a lovely Australian lady in a green suit. She came second in the 400 metres. There's no prizes for coming second in the technology and the research game. If you're ahead, go for it.

The role of Australian radio-astronomers

RB: You said before about "standing on the shoulders of giants," which I think is a Newton quote, and you both come from a radio astronomy background. I've worked in science communications since I joined the Department of Science in '87. It's always amazed me how perhaps unappreciated the radio-astronomy community and achievements of Australian scientists have been over that time. I don't think people really understand just how in high regard radio-astronomy, from Australia, is held around the world. Do you see that?

JO'S: Australia has been one of the small number of global pioneers in radio-astronomy. For the large part, it came out of radar in the Second World War. Australians, under some inspired leadership from people like Joseph Pawsey (1908–1962),[22] have blazed a trail. Many have been right at the forefront in some of the major innovations with things like aperture synthesis, interferometry; we've got quite iconic telescopes like the [Parkes] Dish. I think on a per capita basis, we've punched well above our weight.

RB: Did you like the portrayal of Australian radio astronomy as in "The Dish"? Cardigans and pipes?

JO'S: I found it a bit unfortunate that the Sam Neill character was playing John Bolton (1922–1993), who I'm told was one seriously smart guy. The Sam Neill character, as the scenes do, tended to play him as a bit of a —

TP: Bit of a bumbler.

JO'S: Bumbler.

RB: Yes, he was. A nice guy, though.

JO'S: A story well told.

RB: A very Australian guy.

We'll go to questions from the audience in a moment, so for people who want to have a little think about what they might like to ask John and Terry. While you do that, just a little anecdote.

I was in London last year and I was driving the children of some friends to go and visit the Science Museum, and Archie, who was about 12, was sitting in the back seat. He was very keen to get there to see the Rolls-Royce Merlin engine, which powered the Spitfire and the Lancaster and other aeroplanes. He was rattling off British innovations and he essentially asked, "What has Australia ever invented?" Of course, I thought, Hills hoist, stump jump plough, it's not going to be very impressive. "Oh, wi-fi." That shut up the comments from the backseat.

Australian technology shines

RB: I was just wondering what you think about people like me and probably many Australians taking this joy and taking a bit of reflective glory and pleasure from the fact

21 https://en.wikipedia.org/wiki/Lorraine_Fenton [Ed.]

22 And Ron Bracewell (1921–2007). See Bracewell and Bhathal (2018); Bracewell (1965); and Thompson and Frater (2018) [Ed.]

that we invented wi-fi. Because you must feel proud of that achievement, I imagine.

TP: Yes, I think it's an important thing. Particularly the patent suit which put Australia back on the map in Silicon Valley. Suddenly, they're taking it seriously. A lot of US companies are now getting Australian technology, buying licences from the technology from organisations like NICTA where I was working and CSIRO licencing. It became a lot easier.[23]

I think it's interesting to note, there are uncovered stories out there. Google Maps is another technology that was invented in Australia. The Rasmussen brothers (Lars and Jens) had a little company[24] down in Pyrmont in Sydney. They were doing mapping technology and Google liked it so much, they came and bought it. Google Maps is developed in Sydney still. They built the team up around that. There's another example of an Australian invention we all use all the time.[25]

RB: Yes, all the time. We were unaware.

JO'S: There's a lot of Australians in key positions in Silicon Valley and places like that as well. You mentioned the Rolls-Royce Merlin, I think very often, innovation is driven by needs.

RB: Yes, like radar —

JO'S: Some of the Australian innovations, and there are plenty of them, they're often driven by needs. In mining, we're a global top gun in terms of the technologies used in developing —

RB: CSIRO Data 61, which is the autonomous systems lab, essentially merged with NICTA, has many mining applications and has commercialised these things, 3D mapping of underground mine passages and those sort of things.

JO'S: Yes. Big data is one of the things that is coming, or is here in many ways.

Q and A

Question 1: Very well done there, everybody. Can you possibly explain this concept of a packet arrangement? Isn't it in the transmissions before and after coding, somehow, so it keeps everything in the right order? I'm not that familiar with — it's got a fine beginning and end of certain parts of the transmission so it doesn't get mixed up?

TP: Yes. Getting technical, I guess. Basically, you have to have a header at the beginning of a packet, and an end-of-packet identifier. The packets have to be of certain lengths. You can send short packets or long packets depending on the type of transmission. If you're sending a video, then you send long packets because it's lots of information, whereas for other needs, you'd send shorter packets.

At the packet level, when you're packetising the data, you've got to send it in packets because people move around the room and, again, as people are moving around the

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23 See Brodkin (2012) and Mullin (2012). Mullin's criticisms are undercut by the international awards the team has received. [Ed.]

24 Where 2 Technologies. See Hutcheon (2015). On 19 October 2010, Lars and Jens Rasmussen were awarded the Pearcey Award for NSW ICT Entrepreneurs of the Year. See https://www.pearcey.org.au/awards/state/nsw/2010-nsw-award/ [Ed.]

25 Another is the L4/MIPS microkernel (which is a little piece of software that runs on your phone the moment you press the on button). This was developed at NICTA and the University of NSW, and is in every Snapdragon and Qualcomm processor. [Ed.]

room, the characteristics change, so again, you can't just stream it, you've got to effectively resynchronise it, restart it all the time. It was one of the parts of our invention. Within the packet, we also do what's called interleaving or shuffling the bits around so the DR corrections work better.

Question 2: I was wondering what the royalty monies and the damages, what purpose they were put to? Were they put back into science?

JO'S: About $200 million was used to set up an endowment fund,[26] and that endowment fund is being used to fund research and researchers around Australia, particularly young researchers. That was particularly gratifying to see, that this is hopefully priming the pumps for the next wi-fi. Beyond that, the royalties went back into revenue.

Question 3: Elaine Bean from Adelaide City Council. I would just like to ask, at what point would you consider yourselves satisfied, able to sit on your laurels, where do you think wi-fi will reach its peak?

TP: You should never sit on your laurels. I guess time has caught up with both John and me, who are no longer in full-time employment. We've drawn a line at that level. Wi-fi reach its peak? It's still getting faster and faster. There are different applications, particularly with high-definition video, the 4K video streams.

JO'S: There's another aspect too, I think, technology becomes truly successful when you're no longer aware of it. The plumbing and so forth, we are aware of it at some level, but we don't spend our time worrying about it. I think wi-fi has probably got to that stage. If anything, it has moved towards the sorts of applications that we're using on our devices.

I personally think the thing that's sneaking up on us is that these devices have in recent years become quite intelligent. Much, much more intelligent than we thought of artificial intelligence. Voice recognition is becoming almost as good as humans and lots of other areas, things being done that frankly, I couldn't do.

RB: We've got newspapers replacing journalists with programs that write our articles. It's very hard to distinguish between a journalist-written sports report and a robot-issued one.

JO'S: We can have bots generating fake news now.

TP: Yes, they generate a lot of fake news.

Question 4: During the course of your discussion, you mentioned 4G and 5G, which I've always thought of as being wide-area telephone communications, and we're talking about wi-fi, which is something I use in my home. What's the connection between the two, please?

TP: What I'm saying is the technology that we developed for wi-fi, the methodology, the radio communication systems are now being applied to the wider telecommunications. That technology has now permeated into other areas. The techniques that we used on 2G and 3G couldn't be scaled up to go fast enough for 4G and 5G, so they've come across with the technology that's used in wi-fi.

Question 5: Just following up from the previous question. I think I'm curious as to: has wi-fi gone open source, or does someone own wi-fi still and is driving the technol-

26 The Science and Industry Endowment Fund. [Ed.]

ogy forward, or is it out in the world and everybody gets to develop it from here?

TP: You've got to have standards to have interoperability, so your Samsung phone can talk to your Netgear router. Those standards are put out by the IEEE, based in the US. They issue the standards. There's a standards working group, working on making it go better and faster. The standards are published, so anyone can build something to those standards, but, there again, there's a number of patents covering those standards now. Our patent has expired.[27]

That's the other thing that people don't realise, that a patent has a 17-year lifetime. Our patent expired in 2013. Wi-fi, as itself, the standard is there, anyone can build equipment to that standard. There are other patents out there that people do pay royalties on.

JO'S: Those standards, by the way, have tended to be ongoing work. New standards are being developed, that presuppose the existence of existing standards and in some sense, that is open source, in that anybody can participate in those standards, and standards-making bodies. It's difficult to get your own way for many others.

RB: Must make it an interesting choice as to when you lodge your patent. You want to get it in before anyone else gets ownership of that idea, but you don't want to get it in so early that your 17 years, seemingly a random amount of time, it expires before you've got time to commercialise it properly.

TP: I think the answer is get it in as soon as possible. I think it'd be a brave person to wait.

Question 6: All right. Do you ever think that wi-fi will make something like the NBN obsolete?

TP: No. Simple answer, no. Optical fibre will always go a lot faster. As someone once put it, God isn't making any more radio spectrum. It's already crowded. It is really, really crowded out there. That's part of what you got to make it as fast as possible. You need the backbone. The backbone's filling up, you'd be amazed what the capacity, the hundreds of gigabits on the backbones of the fibres going between the capital cities, going around your streets even. The amount of traffic on the internet is huge.

JO'S: One of the beauties of wi-fi, the original idea, was keep it small. You have a wi-fi access point or whatever you like to call it, and it only covers a small area, like this lecture theatre. That way, you only use the spectrum, the radio waves in this area, and somebody else is free to use it in the next building.

Question 7: This wi-fi kicked off with a very clear goal of generating 100 megabits per second communication. If you had your time over again, could you come up with some other projects you'd think would be similarly clearly stated, that we'll be discussing in 30 years' time?

TP: It's an interesting question. It's always tricky. I think some of the things of interest to me are more again, the applications building on these technologies. Telehealth is my big passion. I've done a lot of work in telehealth over the years. Providing remote diagnosis to people. That's a goal we set ourselves. We developed the technology, it hasn't been taken up particularly well.

27 See https://salsa.digital/insights/global-innovators-since-the-1990s (16 January 2017) [Ed.]

I think the 100 megabits was a nice clear number, that helped a lot.

JO'S: I usually answer a question, "what do you think's coming next?" with "ask somebody younger than 14."

Question 8 (RB): This was a question someone asked me to ask here. There are two sides of the internet, one where it's a dark and dangerous place full of extremist groups and terrorists and fake news, like you said before, or one thing that makes the world smaller, brings us all together, makes us all more connected and productive and happy and nice. Do you have a reflection on that?

JO'S: I guess my take is, it's facilitated both the dark and the light sides of human nature, I'm afraid.

RB: It reflects us.

JO'S: It reflects us. I do watch with some horror what's happening with fake news and the way it's influenced some recent events. You wonder whether the law has to catch up with some of these things, should we be free to say things that —

RB: The nasty word, regulation, maybe in some way.

JO'S: On the other hand, you're already struggling under too many regulations.

RB: How do you regulate the internet?

JO'S: Yes.

RB: We don't have flying cars yet. Maybe just one or two, but they're not commercially available. We don't have hover boards that don't explode. Is there anything else you see coming up? You would be talking with inventors and technologists all over the world, I suspect.

TP: Yes. I think that the one problem that hasn't been cracked is the home control, home networking control. People talk about the internet of things and all the data that's being generated, I think a lot of that is overblown hype. I think the problem is, technologies haven't come up with a way to make it invisible. I think John touched on this earlier. It has to be invisible. It can't be all this mishmash of things.

A few years ago, I automated one of our display areas at our place of work, and I had two very smart engineers working on it for three months to get it working properly with the lights swapping and things changing as you went. That's just crazy. I think that's an area that's going to have to change.

I think the other area is education, very important with technology. There was a big push about three years ago for open universities and online courses you could enrol at MIT or you could enrol at Stanford. That's gone very quiet at the moment.

JO'S: I think the sense I have is, a lot of young people are looking at online courseware, and it's putting some big pressure on —

RB: On the university.

JO'S: … Anybody, but the number one is universities, high-ranked ones. It's getting the accreditation. Anyway.

TP: I think using the internet for access to information is so important.

RB: Yes. That would be great for global productivity, lifting people out of poverty, education is obviously key. Education and health.

TP: More laptops with wi-fi in schools, that's my answer.

RB: Now that the royalties have finished.

TP: Yes.

Conclusion

RB: I think we've run out of time. It's been a great pleasure having a chat to you both and sharing your observations. An hour is obviously nowhere near enough to get into any detail. It's been wonderful to hear your observations and your recollections.

Please join me in thanking Dr Terry Percival and Dr John O'Sullivan for being here today. Thank you.

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The COVID-19 pandemic: losing the race

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Introduction[1]

The first case of COVID-19 arrived in Australia on 19 January 2020 (Hunt 2020). But the beginning of the end of what would become the COVID-19 pandemic occurred just over a week earlier on 11 January. It was on that day that a consortium led by Professor Zhang at Fudan University in Shanghai announced to the world — via a tweet by Eddie Holmes FRSN[2] — that they had sequenced the coronavirus genome from the Wuhan outbreak.[3]

In that DNA sequence lay the building blocks of vaccines against the virus, and with it what would turn a once-in-a-century pandemic into a comparatively routine public health challenge. The journey from a collection of bases that began "attaaaggtt" to near-universal jabs in arms had plenty of steps in between. And those steps weren't simple. Vaccines had to be developed, tested in three different phases of clinical trials, manufactured, distributed and injected. The challenge for policymakers around the world was to transform those steps from being complicated to being inevitable. They needed to convert mass vaccination from a possibility into a certainty.

The good news for Australian policymakers was that the hard parts of this process were either already done, or being done remarkably effectively overseas. Back in 2005, Drew Weissman and Katalin Karikó from the University of Pennsylvania had developed a technique to produce customised "messenger ribonucleic acid" (mRNA) that could instruct cells in the human body to produce any sequence of proteins that scientists wanted. They had patented this technique in 2006 — and that patent was eventually licensed to Pfizer and Moderna to create the COVID-19 mRNA vaccines.[4]

On 15 May 2020, President Donald Trump announced a public-private partnership dubbed Operation Warp Speed to coordinate and accelerate the development of COVID-19 vaccines. This program provided US$11 billion in funding to eight companies to develop and test vaccines. And, crucially, it included so-called "advance purchase agreements," whereby the US government would pledge to purchase a certain amount of the vaccines once they were developed,

1 This is an edited version of Chapter 3 of the authors' *Australia's Pandemic Exceptionalism: How We Crushed the Curve but Lost the Race*, Sydney: NewSouth Publishing, 2024. Reprinted with permission.

2 See Holmes (2021) [Ed.]

3 The full genetic sequence was subsequently posted at GenBank, https://www.ncbi.nlm.nih.gov/nuccore/MN908947.

4 Karikó and Weissman were jointly awarded the Nobel Prize in Physiology or Medicine 2023 for their discoveries that enabled the development of effective mRNA vaccines. [Ed.]

tested, and approved by the Food and Drug Administration (FDA). For instance, on 22 July 2020, the US government placed an advance purchase order of US$2 billion with Pfizer for 100 million doses of its vaccine.

On 12 April 2020, Bill Gates had pointed out that manufacturing facilities needed to be put in place while the vaccines were being developed, rather than waiting to discover which vaccines would work and then scaling-up specific facilities. As he put it (Gates, 2020):

> We aren't sure which vaccines will be the most effective yet, and each requires unique technology to make. That means nations need to invest in many different kinds of manufacturing facilities now, knowing that some will never be used. Otherwise, we'll waste months after the lab develops an immunisation, waiting for the right manufacturer to scale up.

Indeed, the Gates Foundation committed hundreds of millions of dollars to do exactly this — build the vaccine supply chain even before there was vaccine supply (Bill and Melinda Gates Foundation, 2022).

So, the critical elements of successful vaccines had been put in place. There was vaccine development to be done and clinical trials to be run, but the table had been set and drug manufacturers had powerful commercial incentives to move quickly and effectively.

Australia's three tasks

What then, one might well ask, was there left for Australia to do? Three things. First, we had to purchase a sufficient and timely supply of whichever vaccine would turn out to be the most effective. Second, we had to convince the Australian public to get vaccinated. And, third, we needed to quickly and efficiently get jabs into arms. All three elements were essential for Australia to exit the pandemic. On this test for policymakers, there was no partial credit. They had to nail all three.

What the Australian public got from its leaders was a stellar performance on the second and third elements, and abject failure on the first. Since we needed all three, ultimately our government failed us.

This failure unnecessarily prolonged the pandemic in Australia. It cost hundreds of lives. And the additional lockdowns it necessitated cost the nation more than $30 billion in direct economic costs alone — and billions more in indirect costs (Holden & Leigh, 2022). It was a failure that was immortalised in one, succinct, memorable and profoundly stupid phrase from Prime Minister Scott Morrison. On 10 March 2021, Morrison said of the vaccine rollout, "This is not a race." He went on to repeat that phrase four times that month (Taylor, 2021).

But it *was* a race. It was a race to end the pandemic. It was a race to save Australian lives and to reopen the economy. It was a race to put lockdowns behind us. And it was a race that we could have won, but failed to as a result of poor preparation, bureaucratic failure, and an absence of political leadership.

As Jane Halton, secretary of the federal health department from 2002 to 2014, chair of the global Coalition for Epidemic Preparedness Innovations, board member of the government's National COVID-19 Coordination Commission during the pandemic, and head of the 2022 Review of COVID-19 Vaccine and Treatment Purchasing and Procurement, now says:

> It was a race. It was always a race. Manifestly, we had longer lockdowns than

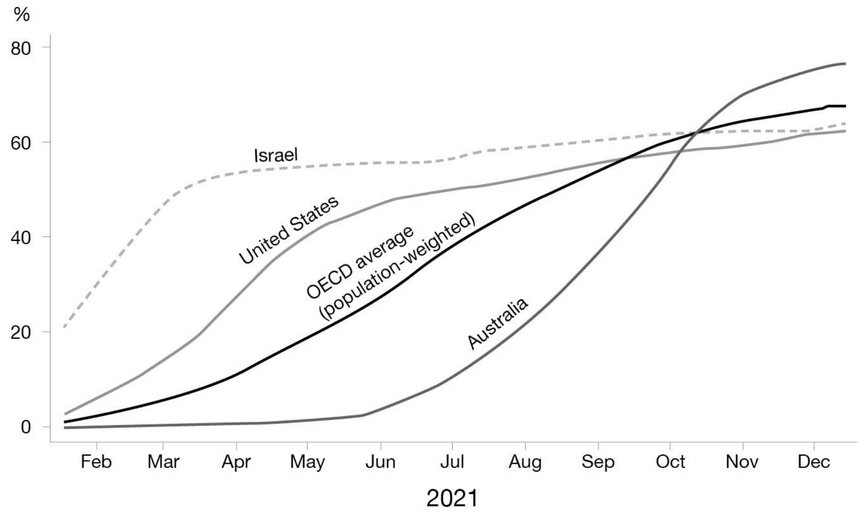

FIGURE 3.1 **Comparative vaccination rates**
SOURCE Holden and Leigh (2022).

NOTE If no children are vaccinated, the adult vaccination rate is approximately 15–20 percentage points higher than the overall vaccination rate.

> we actually needed to have because we didn't have supply and rollout as quickly as others.[5]

Once Australia did get moving, our vaccination rates were world leading. As Figure 1 shows, as late as June 2021 Australia had hardly vaccinated anyone, and severely lagged behind countries like the United States and Israel. By October — just four months later — Australia had erased that deficit and continued to vaccinate more and more of the population.

Yet for far too long Australia's vaccination rate was dismal. Figure 1 demonstrates that the population-weighted average vaccination rate among advanced economies (the 38 OECD countries) was well above Australia's for the greater part of 2021. Shockingly, in mid 2021 just 6% of the Australian population had been vaccinated, compared to the average among OECD countries of 32%. But even this understates the magnitude of our vaccine failure. For more than two months in 2021 Australia had the very worst vaccination record among all OECD countries.[6] We weren't first. We weren't among the best. We weren't above average. We weren't a bit below average. We were stone-cold last. We did worse than Mexico, Turkey and Portugal, to name just a few countries with far lower levels of economic development and traditionally far less functional administrative states.

Australia did not face significant vaccine hesitancy among its population — some-

5 ABC TV, Nemesis, series, https://iview.abc.net.au/show/nemesis/series/1/video/NS2412H003S00

6 As Holden & Leigh (2022) document, from 12 May 2021 to 26 July 2021, Australia ranked last in vaccination rates among OECD countries.

thing that dogged other countries, like the United States. We didn't have any serious politician expressing the view that Australians should not be vaccinated. We had a long history of compulsory vaccination against childhood diseases like measles, mumps and rubella. Evidently, we had a government willing to marshal massive economic resources to combat the pandemic.

But we pursued a flawed vaccine strategy from the very start. Rather than ensure a large supply of all the possible vaccines, we gambled mostly on just two. We pinched pennies instead of buying insurance at a time when insurance was incredibly cheap and the risks we faced were extremely large. We confused industry policy with health policy in trying to back the University of Queensland vaccine and the manufacturing capabilities of CSL. When it came to our vaccine procurement strategy, we did everything wrong. And this isn't just obvious with 20:20 hindsight: it was abundantly clear at the time. Getting the vaccine purchasing strategy right didn't require specialised medical knowledge or negotiating prowess. All it required is the sort of basic economic logic that is taught to first-year undergraduates.

Australia's vaccine procurement strategy

There were eight companies that were supported in vaccine development under the US government's Operation Warp Speed. In principle, Australia could have placed orders with all of these companies. We could have done so early. And we could have bought enough doses from each of the companies to guarantee that every Australian could be vaccinated as soon as the first successful vaccine was available. To paraphrase former Treasury Secretary Ken Henry's dictum about stimulus during the 2008 financial crisis, that three-pronged strategy could be described as "Go broad, go early, go ample."

Instead, we did the opposite. Our vaccine purchasing strategy was selective — it initially focused on just four vaccines (but principally two). The timing of purchases was sluggish, even for the favoured AstraZeneca and UQ vaccines: those agreements were first announced in September and October of 2020, respectively, while other countries had moved as early as July 2020. That might not sound like a long time, but in the context of a pandemic it absolutely was. Moreover, the first deal with Pfizer for its Comirnaty mRNA vaccine was not reached until November 2020. A deal with Novavax for its protein vaccine was also announced in November. And the initial vaccine purchases were not sufficient to cover the entire Australian population. The initial deal with AstraZeneca was for just 33.8 million doses which, given that two doses per person were required, covered fewer than 17 million Australians (even before considering wastage, spoilage and other factors). Worse still, the initial Pfizer contract was for just ten million doses, covering at most five million Australians. There were no orders at all in 2020 for the Moderna vaccine, and an agreement was not reached until — startlingly — the middle of 2021.

Until 13 May 2021, Australia did not have agreements in place for sufficient doses of what turned out to be by far the most effective COVID-19 vaccines — the mRNA vaccines produced by Pfizer and Moderna — to cover the entire Australian population. That's roughly nine to ten months later than should have been the case under any competent vaccine procurement strategy. In the context of a pandemic, that's an eternity.

As a group of Geneva-based epidemiologists put it (Choiseul et al., 2021):

> [G]iven the very aggressive and initially successful response of Australia to the COVID-19 epidemic, the government's investment in the vaccination campaign is relatively low … It could have been expected that Australia would take all possible measures to immunize its population as soon as possible.
>
> Observing the vaccine strategies of other high-income, high-resource countries over the same time makes it clear that Australia could have invested its money into vaccine acquisition more wisely … The choice of entering into advance-purchase agreements with only three manufacturers … was risky.

The auditor-general's report on Australia's vaccine rollout documents this in precise detail, and makes for excruciating reading (Australian Auditor-General, 2022). The key table from that report provides the timeline of Australia's vaccine purchases, and it is reproduced in Table 1.

The obvious response to this critique of Australia's vaccine procurement strategy is that it looks at the situation in hindsight. Indeed, as noted earlier, Prime Minister Scott Morrison described those who were critical of Australia's vaccine procurement as "hindsight heroes"(Gould, 2021). But, as we pointed out at the time, the real issue wasn't being right in hindsight. It was the staggering lack of foresight by the government that was the root of all our problems (Hamilton & Holden, 2022).

In fact, even thinking that hindsight could be a factor here reveals the mindset that led to our calamitous strategy in the first place. Start with the basic facts surrounding vaccine purchases in early 2020. First, there were as many as eight credible candidate vaccines and it was unclear which of these were going to turn out to work, how high the efficacy was going to be, and on what timeframe the development would occur. Second, the social and economic benefit of effective vaccines was going to be extremely large relative to the cost. The costs of lockdowns, deaths, social dislocation, loss of education, and the need for ongoing fiscal support added up to billions of dollars *per month*. The cost of the best (mRNA) vaccines was about US$30–$39 per dose. That's less than A$2 billion to cover all 25 million Australians, without deaths, social dislocation, loss of education, and the need for ongoing fiscal support added up to tens of billions of dollars *per month*. The cost of the best (mRNA) vaccines was around US$30–$39 per dose (Lelani et al., 2022). That's less than A$2 billion to cover all 25 million Australians, without trying to negotiate a discount[7]. Even if we assume that cost for all eight potential vaccines, we're talking about $16 billion — or less than two months' worth of the social and economic costs. Third, we were in competition with other countries to get doses fast. A race, if you will. European regulators were talking about export controls. The United States was acting decisively. Canada bought six

7 The true cost would almost surely have been substantially lower. As Holden & Leigh (2022) report: Pfizer's former president of global research and development, John LaMattina, observed that "In the case of Australia, enough vaccine to inoculate its entire population over the age of 18 should have been done at once. Assuming that is about 20 million Australians, this would have cost about US$780 million."

Table 1: Australia's vaccine purchases

Vaccine	Number of doses per agreement[a] (millions)	Total number of doses per vaccine (millions)	Date agreement announced	Vaccine type	Approved by TGA
AstraZeneca (Vaxzevria)	33.8		2020-09-07	Viral vector	2021-02-15
	22.5	56.3	2020-12-11		
University of Queensland	51.0	51.0	2020-10-08	Protein	no[b]
Pfizer (Comirnaty)	10.0		2020-11-05	mRNA	2021-01-25
	10.0		2021-02-04		
	20.2		2021-04-09		
	0.5[c]		2021-05-13		
	85.0		2021-07-25		
	1.0		2021-08-15		
	0.5[d]		2021-08-31		
	4.0[e]	131.0	2021-09-03		
Novavax (Nuvaxovid)	40.0		2020-11-05	Protein	2021-01-19
	11.0	51.0	2021-12-11		
Moderna (Spikevax)	25.0		2021-05-13	mRNA	2021-08-09
	1.0[f]	26.0	2021-09-01		
Total number of doses purchased (millions): 315.3					
Total number of doses purchased that received TGA approval (millions): 264.3					

Source: Australian Auditor-General (2022).
Note a: Agreements include advance purchase agreements with vaccine manufacturers and agreements with nations to purchase additional vaccine stock.
Note b: The University of Queensland vaccine did not proceed past human trials in December 2020.
Note c: 513,630 Pfizer doses purchased from the COVAX facility.
Note d: 500,000 Pfizer doses were "swapped" with Singapore in August 2021 and repaid in November 2021.
Note e: Four million Pfizer doses were "swapped" with the UK in September 2021 and repaid in late 2021.
Note f: One million Moderna doses were purchased from EU member states in September 2021.

times the number of doses required for its population. Fourth, "excess" vaccines weren't going to be wasted. They could easily have been resold. Better still, being able to distribute those doses as foreign aid to less wealthy countries in the Asia-Pacific would have been both a diplomatic triumph and, well, the right thing to do.

None of these four factors required hindsight. They were all completely obvious in early 2020. The government could simply have heeded Bill Gates' crystal-clear advice back in April 2020. Yet Australia somehow managed to bungle it. Remarkably, the story doesn't end there. It was subsequently revealed that it wasn't just Australia failing to be appropriately proactive. We were given a second opportunity by Pfizer. It was reported in early September 2021 that "Pfizer contacted the health department on 30 June 2020 to request a formal meeting with Health Minister Greg Hunt to discuss supply contracts. Instead, it was taken by a bureaucrat ten days later" (Gould, 2021). Clearly it wasn't a priority.

Stephen Duckett, health economist and former secretary of the federal health department, agrees that the government's strategy was risky, and that this would have been obvious at the time to anyone who understood economics:

> I was critical of it because most other countries were doing a portfolio strategy, hedging their bets, investing in a number of vaccines. We had a very narrow strategy, which is a risky one. And it turned out to be very risky. You've got to be careful about hindsight. We didn't know at the time whether mRNA would work; we didn't know which vaccines might work, which might not. But even at the time, looking forward, most other countries had more options. Many countries took multiple options. And we didn't, we took a very narrow set of options. And you would have known at the time that that's unlikely to be a good strategy because of economic theory.[8]

Moreover, it simply cannot be claimed that the government didn't receive fair warning. In June 2021, a slide deck prepared for the government by consulting firm McKinsey & Company (of which Greg Hunt was a former employee) was released under freedom of information (McKinsey & Company, 2020). Delivered on 27 August 2020, the month before the government announced its first orders, the document laid out comprehensively the race the government faced, including timelines for the availability of all vaccine candidates and the orders already placed by different countries by that time. And Jane Halton says she warned the then health minister of these risks:

> I was seeing on a weekly basis what was happening in the vaccine supply chain world, which showed progressively more and more of the potential supply of vaccines being hoovered up by other countries. And so I was saying to people in government that this was very worrying. And I certainly told Greg Hunt.[9]

On every dimension that mattered for vaccine procurement, Australia got the cost-benefit analysis badly wrong. It might, at first glance, seem expensive to buy all eight

8 Stephen Duckett, Zoom interview, 2 April 2024.

9 ABC TV, Nemesis, series, op. cit.

candidate vaccines. Wasteful, even. Why not just buy one? The answer, of course, is that it was unclear which vaccine would be best — or would even work at all. A basic tenet of investing is that it is best to diversify one's portfolio. This is why it is wise to buy a basket of stocks, rather than bet on just one. Indeed, it is the rationale for buying the entire stock market index rather than trying to pick individual stocks. And it is why "stock picking" active funds rarely systematically beats a broad stock-market index. Anyone who has studied undergraduate finance, or who has even received basic financial advice, would understand that betting on just two out of the eight potential vaccines was a bad idea. But even if nobody involved in Australia's vaccine purchasing possessed this basic knowledge, surely they knew of the adage "don't put all your eggs in one basket."

Now it might have seemed wasteful to have 50 million doses of *both* candidate mRNA vaccines. After all, if the Pfizer mRNA technology worked, then there was a pretty good chance that the Moderna mRNA technology would also work out. After all, they were both based on the same underlying approach. Indeed, this was part of the thought process — to the extent that there was one — behind the decision to purchase just one vaccine from each of the major categories. We bought Pfizer over Moderna (mRNA vaccines); AstraZeneca over Johnson & Johnson (viral vector vaccines); and, after the University of Queensland vaccine fell over, Novavax over Sanofi (protein vaccines) (Hamilton & Holden, 2021a). This implicitly assumed that the success of vaccines within a particular technology was perfectly correlated. In other words, if AstraZeneca's vaccine succeeded, then Johnson & Johnson's would also succeed with 100% probability. That ignored the differences in approaches among vaccines that used similar underlying technology. It ignored the differences in speed to market among different vaccines. It ignored the differences in manufacturing processes that could lead to different success profiles. It ignored inevitable differences in distribution. And it ignored the potential differences in the eventual efficacy of vaccines using the same underlying technology. In short, the "buy one from each category" approach treated apples and mangoes as if they were interchangeable just because they are both types of fruit.

What about timing? One might argue that it wasn't necessary to commit to vaccine purchases while they were still in development and going through lengthy clinical trials. But this misses the fact that vaccines were always going to be in limited supply soon after approval and those countries that got in early were going to be first in the queue. By the time it was clear which vaccines were going to be successful, it would be too late to purchase significant quantities quickly. Moreover, the advance purchase agreements provided much-sought-after funding for the companies involved, as they went through clinical trials, which could cost into the billions of dollars.[10]

So why did Australia make such grave errors when it came to vaccine procurement? There's no question that Prime Minister Scott Morrison and Health Minister Greg Hunt bear ultimate responsibility. They were the leaders charged with making

10 For instance, the Pfizer phase-3 clinical trial involved more than 46,000 participants at 153 sites in six countries, https://www.pfizer.com/science/coronavirus/vaccine/about-our-landmark-trial

the extremely consequential decisions about vaccine procurement. They might have received lousy advice, but they absolutely should have known better.

And what about that advice? Chiefly responsible for the vaccine rollout was federal Chief Medical Officer Brendan Murphy. Indeed, it was Murphy who first used the "it's not a race" metaphor (Hamilton & Holden, 2021e). He made that remark in early March 2021 when people were finally starting to ask questions about our off-the-rails vaccine rollout. As we noted at the time (Hamilton & Holden, 2021c):

> Confronting delays in the COVID-19 vaccination program this week, federal Health Department secretary Brendan Murphy said: "We're not like the US or UK." He's right, but not in the way he intended.

And although Murphy justified this approach by saying that the vaccine rollout should proceed "as quickly and carefully and safely as we can" — which seemed to imply that moving at a comparable pace to other competent countries around the world was unsafe — he was acting less as an adviser and more as a politician. He seemed almost to be covering for the government's flailing vaccine rollout. He was making a subjective statement about policy trade-offs, not providing objective medical advice.

Stephen Duckett believes an "optimism bias" driven by inside-the-bubble thinking in the health department ultimately led to the failure:

> I think major investment in two vaccines and not hedging your bets is stupid. So I've been trying to work out: why did they do it. You've got to go back to where they were sitting in 2020 when these vaccine decisions were being made. If you are sitting there, you will say CSL has a track record of delivery in vaccines. So if we invest heavily in CSL that is very, very safe. And so do we really need to have any insurance in those other strategies? I think that was an error.
>
> And don't forget the impact on their psyche of the Melbourne research establishment, of which CSL is part. The people they were talking to would have been saying: "CSL can do this, we've got these huge vats, we can make unlimited numbers." The chief scientific officer of CSL would have been talking to Brendan Murphy; they would know each other. And Brendan would have felt reassured that CSL knew what they were doing and were able to do it. And this was safe. But that doesn't mean you don't invest in it anyway. The fact that they didn't have a backup? I have no idea why they went for such a narrow strategy.[11]

What emerged from that rich brew of optimism bias, bad advice, and self-congratulation, completely devoid of basic economic logic, was a dangerous level of groupthink that not only excused Australia's vaccine failures but celebrated them. Rather than admit to mistakes and acknowledge the need to improve, the Morrison-Hunt-Murphy triumvirate rewrote history in real time. This put Australia in an incredibly dangerous position. Our vaccine strategy wasn't conservative and it wasn't safe. It was dangerously unsafe. We were effectively gambling on there not being a major outbreak or a new strain of the virus emerging for another six months. Again, this was clear

11 Stephen Duckett, interview.

at the time. We noted these risks in early March 2021, commenting on the Murphy-Morrison "it's not a race" dogma (Hamilton & Holden, 2021c):

> If that thinking extends to a lack of ambition about the proportion of Australians we vaccinate, then at best we'll squander a remarkable opportunity, and at worst risk another major outbreak and threaten the nation's prolonged economic recovery. If it reflects any complacency about the urgency of the vaccination program, it is terribly dangerous.

Australia had a remarkable opportunity in early 2021. Unlike the United Kingdom and the United States, we did not have significant caseloads. Those countries had to vaccinate to save lives in the short term. By contrast, Australia had the potential to vaccinate enough of the population to achieve so-called "herd immunity" — the point at which a sufficient proportion of the population had been vaccinated that an exponential outbreak could not take off.[12] What it would have taken to achieve that enviable outcome — herd immunity without the extreme human toll stemming from mass infection — was to have enough doses of the best vaccines ready to go, and an efficient distribution mechanism in place to get needles into arms.

At this point in the evolution of the pandemic, it was clear that Australia's defective vaccine strategy was causing major practical problems. Having failed to purchase nearly enough of the mRNA vaccines, we were left with the AstraZeneca vaccine, which had been shown to have lower efficacy. Much better than nothing, to be sure, but not close to as effective as the mRNA vaccines that we had not ordered nearly enough of. This had a direct impact on the proportion of the population that needed to be vaccinated in order to achieve herd immunity and eliminate the possibility of an exponential outbreak.

Epidemiologists had long understood the link between the efficacy of a vaccine and the proportion of the population that needs to be vaccinated to achieve vaccine-induced herd immunity. As early as December 2020, UNSW Kirby Institute epidemiologists MacIntyre, Costantino, and Trent released a pre-print showing exactly how the herd-immunity threshold varies with vaccine efficacy. They showed that at 95% efficacy just 63% of the population would need to be vaccinated to achieve herd immunity. But if the vaccine in question only had an efficacy of 70%, then the vaccination threshold required for herd immunity rose to 86% (MacIntyre et al., 2020).

These numbers were extremely pertinent. The AstraZeneca vaccine — on which Australia had largely pinned its hopes — had an efficacy in clinical trials of 72% (although some early "real-world" data around that time showed higher rates of efficacy). By contrast, the Pfizer mRNA vaccine had a stunningly high efficacy of 95%. Yet in March 2021 we had only ordered enough

12 As we put it in March 2021: "As of Friday, about 130,000 Australians — or one in 200 — had received a first-dose COVID-19 vaccine. And this week the government admitted it would not meet its target to complete the vaccination program by the end of October. Countries with significant caseloads, such as Britain, the US and much of Europe, are vaccinating to save lives today rather than reach for so-called 'herd immunity' — the point at which so many people have been vaccinated that another exponential outbreak can't occur. Australia, by contrast, has a real chance to achieve herd immunity. Whether we do so will be determined by government policy." (Hamilton & Holden, 2021c).

of the Pfizer vaccine to cover at most 40% of the population (without accounting for wastage, spoilage and overdosing, all of which were both commonplace and already occurring). And Australia had failed to order a single dose of the other extremely high-efficacy mRNA vaccine, produced by Moderna. With the mix of vaccines we had at that point, we needed to vaccinate about three-quarters of the population in order to achieve vaccine-induced herd immunity.

This made our vaccine race even longer. Rather than having to vaccinate just 63% of the population, we needed to vaccinate 75% of the population. That amounted to an additional three million people who we needed to convince to get vaccinated, get them to show up to a vaccine hub, and get them to come back several weeks later for their second shot. Even if we could be sure a sufficient number would show up, that would inevitably take time, so this lower efficacy simply pushed out the date by which we could reach an adequate level of protection to avoid lockdowns. This put us at risk of another wave arriving in the meantime. In the end, as Table 1 (above) highlights, it wasn't until 9 April 2021 that the federal government got its act together to purchase an additional 20 million doses of the Pfizer vaccine (enough for ten million Australians), and not until 13 May that it ordered 25 million doses of the Moderna vaccine.

The cost of Australia's vaccine debacle

It would turn out that the months between when mRNA vaccines were available (and countries that had made sound purchasing decisions were vaccinating their populations) and when Australia finally had enough doses of those vaccines to cover the Australian population were crucial months. To get a sense of the economic impact of our dismal vaccine rollout, consider what might have happened had we been as competent as Israel in procuring vaccines.[13]

Israel's last lockdowns ended in February 2021, so it is reasonable to think that, had our vaccine procurement been comparable to Israel's, then we, too, could have avoided lockdowns from this point on. What did that cost in a pure, but rather narrow, economic sense? More than $30 billion.

To see why, start with this. The Australian Treasury has estimated that the economic cost of nationwide lockdowns was $3.2 billion per week (Australian Treasury Department 2021). It's important to remember that this is the cost of lockdowns relative to a counterfactual scenario where there was no lockdown *and no pandemic*. It is emphatically not the cost of lockdowns compared to just "letting it rip" in the middle of a pandemic. This is also — and Treasury duly acknowledges this — an underestimate. It focuses only on direct economic effects, and doesn't factor in indirect effects like drops in consumer confidence (which reduce economic activity by making consumers reluctant to spend), supply-chain disruptions (which reduce economic activity by making it harder for consumers to spend even if they want to), and it ignores the economic cost of government support programs.

The lockdowns that took place between March and December 2021 — which could have been avoided had our vaccination strategy and rollout been up to scratch — were

13 The following method of calculating the economic costs that could have been avoided follows Holden & Leigh (2022).

the equivalent of a 68-day nationwide lockdown (Holden & Leigh, 2022). At a direct economic cost of $3.2 billion a week this shakes out to $31 billion.

Not only does this lower-bound estimate exclude the important indirect economic effects mentioned above, it also excludes the social impact of the vaccine-avoidable lockdowns. While it is hard to quantify exactly how large these were, there were some very tangible effects. Perhaps the most obvious was the school closures that resulted from the lockdowns. Not only did this damage the human capital of all school students, it also reduced the productivity of parents who were attempting to work from home while simultaneously acting as de facto teachers. There is some reason to believe that many students managed to recover the learning loss from this period, but parental productivity, by its very nature, was permanently lost.

Taking together the direct economic effects, the indirect economic effects, and the school-closure effects of the lockdowns that our substandard vaccine strategy caused, the cost to the Australian economy was almost surely north of $50 billion. Perhaps well north of that. As such, it was easily the single largest public policy mistake in Australian history. Indeed, at around 10% of GDP, the vaccine debacle was more than half as large as the 17% drop in GDP during the Great Depression of 1929–31 (SGS Economics & Planning, 2020). So, as an economic matter, that makes Australia's great vaccine debacle almost surely the single most costly *economic event* in Australian history. And unlike the Great Depression, or the World Wars, or the financial crisis of 2008, it was completely self-inflicted. An unforced error of the gravest kind.

Plenty of blame to go around

As if the federal government's bungling wasn't enough, other officials managed to undermine vaccination efforts by damaging public confidence. The most serious example was Queensland Chief Health Officer (and now state Governor) Jeannette Young. In a June 2021 press conference, Young managed to raise serious doubts — at least in some people's minds — about whether they should be vaccinated.

The ostensible issue, to the extent that there was an issue, was the possibility of the AstraZeneca vaccine potentially causing blood clots in young men. The key remark that Young made in her press conference was the following (Zillman, 2021):

> I don't want an 18-year-old in Queensland dying from a clotting illness who, if they got COVID, probably wouldn't die.

This would turn out to be a profoundly misguided remark. At the time Young made it, there had been two Australian deaths linked to the AstraZeneca vaccine, from a rare clotting disorder known as thrombosis with thrombocytopenia syndrome, or TTS. The first two deaths from TTS were a 48-year-old woman in April 2021, and a 52-year-old woman in June (Davey, 2021b). The rate of TTS was very low, and continued to be very low. In September 2021 the Therapeutical Goods Administration (TGA) reported that TTS occurred in just two people out of every 100,000 who received the AstraZeneca vaccine (DHAC, 2021e). And most of those TTS cases were both treatable and were treated, with a vanishingly small number resulting in death. The TGA currently summarises that, from an individual's perspective, "The protective benefits of vaccination against COVID-19 continue to far outweigh the potential risks of vaccination" (DHAC, 2023).

Not only was vaccination in an individual's own interest, despite the small chance of TTS, it was also in the social interest. By preventing the spread of COVID-19 to others, vaccination would reduce overall COVID-19 deaths. So not only was Young giving bad medical advice to individuals, she was giving absolutely terrible public health advice. And giving sound public health advice was, well, her one job.

But it was all too understandable that if you were an 18-year-old listening to her advice — or a 50-year-old for that matter — you might hesitate to get vaccinated. And that was precisely the damage. Officials like Young had tremendous power to shape public opinion during these frightening times. And in light of the mistakes that the federal government was making, it was even more important that state chief health officers were aiding the vaccination effort, rather than hindering it.

Rather than remedy her mistake, Young then both doubled down and made a further mistake. In a clumsy attempt to defend her remarks, Young said (Smee, 2021):

> I am giving my advice. I am a doctor. I've been involved in Australia's vaccination program now for 16 years. I have the vaccination rate here for our little ones up to five years old up to 95%. I am on the record as supporting vaccination. But I want the right vaccine to go to the right person ... This is my advice. People, of course, can go and get their own advice. They can get it from wherever they wish to get it, but my advice is very, very clear.

And she later went on to say (Layt, 2021):

> I firmly believe that younger people — and I said 18-year-olds in that comment — should be getting Pfizer ... I do not think they should be getting AstraZeneca. And we have plenty of Pfizer and they can come out and get Pfizer, or Moderna.

The stocks of Pfizer obviously depended on how many people wanted to access them. And if people suddenly became afraid of taking AstraZeneca at that time, then there would not have been "plenty of Pfizer." In fact, anti-vax posters quickly emerged in Melbourne with a picture of Young and her words "I don't want an 18-year-old in Queensland dying from a clotting illness who, if they got COVID, probably wouldn't die." Young had played right into their hands (Layt, 2021).

It would be remiss of us not to mention that federal Health Minister Greg Hunt played his own part in slowing vaccination by casting doubt on the AstraZeneca vaccine and sending the message that it was OK for those under 50 to wait until later in the year to be vaccinated. In May 2021, Hunt told ABC radio host Michael Rowland (Davey, 2021a):

> Right now, we want to encourage everybody over 50 to be vaccinated as early as possible. But we've been very clear that, as supply increases later on in the year, there will be enough mRNA vaccines for every Australian.

In just two sentences — speaking with the authority of the federal health minister and with the imprimatur of knowledge — Hunt had managed to undermine the vaccine rollout. And, like Young, his efforts — such as they were — to clean up his remarks were likely ineffectual. Bells can't be unrung.

Australia's medical-regulatory complex

The Therapeutic Goods Administration is the body charged with, as they put it themselves, "evaluating, assessing and monitoring products that are defined as therapeutic goods. We regulate medicines, medical devices and biologicals to help Australians stay healthy and safe."[14] And the Australian Technical Advisory Group on Immunisation (ATAGI) is charged with advising "the Minister for Health and Aged Care on the medical administration of vaccines available in Australia" and consulting with "relevant organisations in implementing immunisation policies, procedures and vaccine safety."[15]

The regulation of pharmaceuticals is important. Only the most hardline libertarians deny any role for regulation in this area. Almost all mainstream economists — of which the present authors are two — believe that one of the key settings in which regulation can play an important role is when there are large and important information asymmetries between buyers and sellers in a market. Pharmaceuticals are a classic case. Drug makers have a sophisticated understanding of the efficacy of their products, as well as their potential side effects. Or, at least, they are in a position to collect such information through clinical trials. Indeed, so-called "Phase 3" clinical trials (as well as their smaller-sample precursors, Phases 1 and 2) are required by the FDA before drugs are approved in the United States. International regulators have typically adopted similar approaches.

Among the most famous papers in all of economics — published by George Akerlof in 1970 and titled "The market for 'lemons'" (Akerlof, 1970) — concerns how markets function poorly and can break down completely in the presence of asymmetric information. Akerlof's motivating example was the market for used cars (possible "lemons"), where a seller typically knows a lot more about the quality of their car than does a prospective buyer — but it applies to any market with asymmetric information. Indeed, the market for pharmaceuticals is much larger and more consequential than the market for used cars. It is precisely because the drug market would function very poorly, or completely break down, that regulators like the FDA in the United States and the TGA in Australia exist. So we're not "anti-TGA." But that doesn't mean that regulators aren't deserving of their fair share of criticism.

The TGA's key failure during the pandemic was that it was too slow to approve vaccines for use in Australia. This wasn't just a one-off: it did it again and again with different vaccines. Now you might ask: "What do you mean by too slow? Doesn't that involve a trade-off between risk and reward, between speed and safety?" Indeed, it does. But the TGA wasn't the only regulator making these same decisions. American and European regulators were also balancing speed and safety, and they made very different decisions than did the TGA. Indeed,

14 See Department of Health and Aged Care, Therapeutic Goods Administration (TGA), https://www.tga.gov.au

15 See Department of Health and Aged Care, Australian Technical Advisory Group on Immunisation (ATAGI), https://www.health.gov.au/committees-and-groups/australian-technical-advisory-group-on-immunisation-atagi?language=und

the TGA was persistently behind the curve relative to its international peers.

Toward the end of 2020, vaccines were being rolled out en masse in the United States and Europe. Regulators allowed this by issuing what is known as an "emergency use authorization" (EUA). An EUA is essentially a shortcut to the approval process, allowing approval of a drug (in this case a COVID-19 vaccine) when a large proportion of a Phase-3 trial has been completed (typically more than 3,000 participants), in a public health emergency. It acknowledges the fact that during a pandemic a sensible regulator should adjust the speed-safety trade-off because the costs of delay are so large.[16]

Yet the TGA dithered. It did not approve the Pfizer vaccine until 25 January 2021, more than six weeks after the FDA had approved it. And it didn't approve the AstraZeneca vaccine until 16 January 2021, nearly seven weeks after the UK regulator. And in August 2021 the TGA belatedly approved the Moderna vaccine, a staggering *eight months* after the FDA. This dithering also extended to approvals for children, and for looser cold-storage requirements. The TGA was consistently tardy.

As we wrote at the time, these delays might not sound like much, but they mattered a great deal. The whole point about being in a pandemic is that every moment counts. A major outbreak can be just a day away. Complacency is never OK, but in a pandemic it's deadly. Writing in 2021, we put it this way (Hamilton & Holden, 2021e):

> In case you're wondering "what difference does six weeks make?" think again. Were our rollout six weeks faster, the current Sydney outbreak would likely never have exploded, saving many lives and livelihoods. In the face of an exponentially spreading virus that has become twice as infectious, six weeks is an eternity.
>
> It [the TGA] approved looser cold storage requirements for the Pfizer vaccine, which would allow the vaccine to be more widely distributed and reduce wastage, on April 8, six weeks after the FDA. And it approved the Pfizer vaccine for use by 12 to 15-year-olds on July 23, more than 10 weeks after the FDA.

16 The FDA is explicit about exactly how this trade-off is adjusted. See US Food and Drug Administration, Emergency use authorization for vaccines explained, https://www.fda.gov/vaccines-blood-biologics/vaccines/emergency-use-authorization-vaccines-explained, where it emphasises that: "For an EUA to be issued for a vaccine, for which there is adequate manufacturing information to ensure quality and consistency, FDA must determine that the known and potential benefits outweigh the known and potential risks of the vaccine. An EUA request for a COVID-19 vaccine can be submitted to FDA based on a final analysis of a phase 3 clinical efficacy trial or an interim analysis of such trial, i.e., an analysis performed before the planned end of the trial once the data have met the pre-specified success criteria for the study's primary efficacy endpoint.

"From a safety perspective, FDA expects an EUA submission will include all safety data accumulated from phase 1 and 2 studies conducted with the vaccine, with an expectation that phase 3 data will include a median follow-up of at least 2 months (meaning that at least half of vaccine recipients in phase 3 clinical trials have at least 2 months of follow-up) after completion of the full vaccination regimen. In addition, FDA expects that an EUA request will include a phase 3 safety database of well over 3,000 vaccine recipients, representing a high proportion of participants enrolled in the phase 3 study, who have been followed for serious adverse events and adverse events of special interest for at least one month after completion of the full vaccination regimen.

"Part of FDA's evaluation of an EUA request for a COVID-19 vaccine includes evaluation of the chemistry, manufacturing, and controls information for the vaccine. Sufficient data should be submitted to ensure the quality and consistency of the vaccine product. FDA will use all available tools and information, including records reviews, site visits, and previous compliance history, to assess compliance with current good manufacturing practices."

Sadly, ATAGI was arguably even worse. It issued overly cautious advice about the AstraZeneca vaccine because of concerns about TTS. On 8 April 2021, it advised that Australians aged 16 to 50 should not get the AstraZeneca vaccine, but rather wait (for who knows how long) for Pfizer.[17] Then, on 17 June 2021 it updated this advice to say that those aged 16 to 60 should get Pfizer instead of AstraZeneca (DHAC, 2021d).

ATAGI put far too much weight on a small number of recent events, rather than taking an appropriate statistical view of the risks involved in taking the AstraZeneca vaccine. In the language of statistics, it acted like a *frequentist* rather than a *Bayesian*. Bayesians have a belief based on the existing evidence (known as the "prior probability") about the likelihood of an event, and then update that belief based on whatever new evidence they encounter. Frequentists, on the other hand, ignore the existing evidence and simply require enough data to distinguish signal from noise in judging whether the event will happen. But what if you don't have enough new data and nevertheless must make a decision? Vaccine decision-makers had to make a decision — and a prompt one at that. The only relevant question was how best to make it.

There were four big unknowns when it came to the AstraZeneca vaccine. The first was the probability of an individual (with certain personal characteristics) getting TTS. The second was the probability, conditional on getting TTS, of it not being treated effectively. The third was the probability of contracting COVID-19, conditional on not receiving the AstraZeneca vaccine. And the fourth was the probability of infecting others, conditional on becoming infected.

Doctors and medical scientists knew a lot about the prior probabilities of all of those events. Sure, it was correct to update based on new evidence. But ATAGI went full-tilt frequentist — pretending that it knew nothing about the physiology of TTS or COVID-19, and just ignoring the possibility of an individual infecting others altogether.

As we put it at the time (Hamilton & Holden, 2021e): "This overlooks the fact its recommendations translate into actual protection with a significant lag — eight or more weeks, by which time public health orders inevitably restrain the exponential spread. This has led to frequent and radical updates in advice, leaving the public with whiplash, confused and sceptical."

This was clear from the language ATAGI itself used in its advice. ATAGI's 17 June statement said (DHAC, 2021d):

> From early April to 16 June 2021, 60 cases of confirmed or probable TTS have been reported in Australia. This includes an additional seven cases reported in the past week in people between 50–59 years, increasing the rate in this age group from 1.9 to 2.7 per 100,000 AstraZeneca vaccine doses … TTS is a serious condition in a proportion of individuals who develop it. The overall case fatality rate in Australia (3%; 2 deaths among 60 cases) is lower than has been reported internationally. This is likely to reflect increased detection due

17 Australia's deputy chief medical officer from March to October 2020, Dr Nick Coatsworth, told us in an interview that this decision around the age guidance for AstraZeneca was a significant mistake and hugely consequential. Coatsworth is also of the view that there was a downside to providing an emergency use authorisation in terms of public confidence, which is a legitimate counterpoint to our concern about how critical a six-week delay can be during a pandemic — and indeed was in Australia's case.

> to heightened awareness, as well as early diagnosis and treatment. A spectrum of severity of illness has been reported in Australia, from fatal cases and those with significant morbidity, to relatively milder cases.

Not only was ATAGI getting the cost-benefit analysis wrong purely from the perspective of individuals, it was failing to factor in the impact on other Australians of deterring younger Australians from being vaccinated. In the language of economics, ATAGI, like the TGA, was failing to account for the negative externalities of non-vaccination. In fact the mid-2021 Sydney outbreak, which precipitated the major lockdown, was caused by a limousine driver who had decided not to be vaccinated because — this would be funny if it weren't tragic — he was waiting for Pfizer (Stevens & Parsons, 2021). This led to hundreds of deaths — none of which ATAGI had factored into its analysis.

So it wasn't just that ATAGI was overly focused on individuals rather than the community as a whole. It wasn't just that ATAGI put far too much weight on recent data in Australia compared to the entire stock of scientific knowledge and recent international experience. And it wasn't just that ATAGI ignored the importance of the AstraZeneca vaccine supply given federal government purchasing mistakes. It was that all of these things interacted and compounded. This can be summed up in a single sentence that we wrote of ATAGI in August 2021 (Hamilton & Holden, 2021e):

> At one point, staggeringly, it recommended young people take AstraZeneca — but only if they lived in one of a few local government areas in south-west Sydney.

Vaccine distribution

Procuring vaccines is one thing, but actually getting people vaccinated is another. Both are essential, but they require different skills and approaches. Procurement is largely strategic; distribution and delivery is largely logistical. And while the federal government didn't bungle vaccine distribution as badly as it did vaccine procurement — that would seem impossible — they didn't exactly cover themselves in glory here either. That had consequences.

The federal GP plan

The federal health department and Health Minister Greg Hunt decided early on that Australia's large network of general practitioners (GPs) was the best and most effective means of vaccine delivery. On 7 March 2021, Hunt announced (DHAC, 2021b) that Phase 1b of the vaccine rollout — essentially the vaccination of older Australians and those with serious underlying health conditions — would be conducted through the GP network.

On first inspection, there was a certain logic to this approach. There are more than 6,000 general practices around Australia. GPs have an existing relationship with many of their patients. They are trained professionals, in a position to answer questions and provide reassurance about vaccines. But there were two glaring mistakes that should have been clear well in advance. The first concerned speed. Once vaccines were available, there was a tremendous premium on getting people vaccinated quickly. The GP network, while valuable, was never going to be of sufficient scale to meet the size of the vaccination challenge. Overseas, large sporting venues were being used to vaccinate people at an industrial scale. For instance, in the United States, Dodger Stadium in Los Angeles was contributing to a vaccination rate of three million people per day as early as March 2021. And that was in a country with serious vaccine hesitancy (Hamilton & Holden, 2021d).

Pharmacies that routinely delivered flu shots were not being used in the early days of the vaccine rollout. Incredibly, there was discussion about using pharmacies (of which there were 5,800 across the country) but the federal government was dragging its heels. Hunt announced on 31 January 2021 (DHAC, 2021a) that "Community pharmacy will be an important partner in the rollout of COVID-19 vaccines." What did that mean exactly? It meant that an expression of interest process would soon begin, with the goal of having pharmacies start to deliver shots in May. Hunt seemed to understand the importance of pharmacies, saying that it would "ensure the general population have broader access to COVID-19 vaccinations, provide choice in where the community receive a vaccine, and address barriers to access in some parts of rural and regional Australia."

But then Hunt emphasised the need for caution, making the obvious statement that pharmacies needed to be able to deliver vaccines safely (DHAC, 2021a). Given their track record of safely and successfully delivering other vaccines, this was never really an issue. As Pharmacy Guild of Australia President George Tambassis pointed out (DHAC, 2021a):

> Some 94 per cent of pharmacies are members of the pharmacy profession's quality assurance program, QCPP, and the robustness of this program underpins the sector's ability to meet the challenges of the pandemic and the delivery of COVID-19 vaccinations, while maintaining the levels of service and medicine delivery critical to their role as frontline healthcare professionals.

But Hunt genuflected to the medical-regulatory complex with the following remarks (DHAC, 2021a):

> [P]harmacies will need to demonstrate they meet the highest safety standards and have capacity and capability to deliver COVID-19 vaccines, as well as ensuring they continue to provide important services to their local communities. These standards have been informed by the expert medical advice from the Australian Technical Advisory Group on Immunisation (ATAGI).

The second problem was economics. The government's GP plan involved the peculiar consideration that GPs not "profit" from the vaccination campaign. Why that would be a problem was never made clear. When there is massive demand for services, people are going to make money. As we discuss in Chapter 4 of Hamilton & Holden (2024), testing companies made plenty of money providing PCR tests throughout the pandemic. And, we discuss in Chapter 2, the government put massive resources into economic support programs like JobKeeper.

GPs were required to bulk-bill vaccination appointments, and the reimbursement rates were lower than for standard GP appointments.

For the first six months of the vaccine rollout, there was a so-called Practice Incentives Payment (PIP) program in an attempt to compensate GPs for having to bulk bill. But this was only available to certain "accredited" practices, and the compensation was a mere $10 for giving both of the first two COVID-19 shots to a patient (Wright et al., 2022).

In effect, GPs were being told they needed to shift capacity from higher-remunerating appointments to vaccination appointments. At a time when general practices were already under financial pressure, GPs were being told that they had to take a pay cut to vaccinate Australians — just the opposite of what was needed to catch up after our botched start.

On top of this, the problems with vaccine procurement also impacted GPs, both financially and in terms of their ability to vaccinate their patients. The unpredictability of vaccine supply to GPs led to rescheduling of appointments, lost revenue for GPs, and in some cases missing out on the small PIP bonus by not being able to deliver both of the first two shots (Wright et al., 2022).

In the first month of Australia's vaccine rollout, we were vaccinating only half as many people as were the United States, United Kingdom and European Union in their first months. Having botched vaccine procurement, Australia then went on to start botching the vaccine rollout. As we wrote in March 2021 (Hamilton & Holden, 2021d):

> While we've administered about 250,000 doses, we've imported well over 1.25 million. As challenging as it may be, getting needles in arms isn't rocket science — as overseas experience shows. We had more than six months to plan. There's simply no excuse for anything other than production to be the limiting factor.

The states to the rescue

Stephen Duckett believes the failure of the vaccine rollout ultimately comes down to the federal government's politicisation of it in a bid to wrest the limelight from the states:

> The politics of this were paramount. What we saw every day in the media in 2020 and the first part of 2021 was the Premier and the state Chief Health Officer fronting a news conference. The Commonwealth role was in the economics and the business support, and to a lesser extent summarising nationally what was happening.
>
> What then happened was the Commonwealth saw an opportunity for it to take responsibility for vaccines and vaccinations. So the vaccination strategy became a political strategy. They wanted that to be a Commonwealth-led initiative so that the Commonwealth could get the credit. One of the problems with that is they have more or less no feet on the ground. The states have public hospitals, community health centres, public health units scattered across the state, nurses; so the states had an ability to mobilise a workforce that the Commonwealth didn't have.[18]

When the vaccine rollout finally reached the point of getting jabs in arms, the states stepped up. This would produce one genuine bright spot in the form of the mass vaccination hubs set up by state and territory governments. For instance, on 10 May 2021, New South Wales opened a mass vaccination hub at Sydney Olympic Park. This coincided with adults aged 40 to 49 becoming eligible for the Pfizer vaccine. Staffed with more than 200 registered nurses and operating six

18 Stephen Duckett, interview.

days a week, the hub played an important role in the vaccine rollout. Premier Gladys Berejiklian's remarks at the time demonstrated the appropriate level of urgency:

> We've worked hard to get our systems up and running to make sure we use up every dose we've been given … We want to make sure that if we have any excess doses or we suddenly get doses we didn't anticipate, that we're able to draw on 40 to 49-year-olds that can register from today.[19]

Victoria was similarly effective in setting up vaccination hubs, quickly opening three. The first was opened on 21 April 2021 at the Melbourne Convention and Exhibition Centre, the second in Carlton and the third in Geelong. A fourth was added shortly afterwards in Bendigo. A year into the vaccine rollout, around 20.5 million doses had been delivered at vaccine hubs, on top of the 33.8 million delivered in GP clinics.[20]

In a sense, this wasn't all that surprising. The Australian administrative state had always excelled at practical and logistical tasks. Anyone who has tried to get a driver's licence in both the United States and Australia can attest to Australia's comparative competence: it's a basic matter of state capacity. Establishing vaccine hubs was something that Australian states and territories were well positioned to do quickly and effectively. And, of course, since the states run their health systems, it made sense that they, rather than the federal government, would take the lead here.

Lessons from Australia's vaccine debacle

The chief fault behind our vaccine debacle was the failure to apply basic economic thinking to the problem. In a narrow sense, vaccination was a public health issue. But vaccination really involved risk management and cost-benefit analysis. Yet the reasoning provided behind major decisions — such as the portfolio of vaccines Australia purchased — bore no resemblance to the way economists would think about such problems. It was a most extraordinary false economy. Pennies were pinched in vaccine procurement without any thought that the benefits forgone might be 1,000 times larger. A few million dollars might have been saved by focusing on two vaccines, while tens of billions were lost in the lockdowns — not to mention thousands of lives.

Defenders of the vaccine rollout invariably point to all of the bad luck the government ran into along the way. And it certainly ran into its fair share. If only the UQ vaccine had panned out. If only the Europeans hadn't blocked the export of Australia's contracted AstraZeneca doses. If only the clotting issues hadn't arisen with AstraZeneca. But this "bad luck" is in fact the clearest evidence we have of the government's failure.

It is precisely because some amount of bad luck is bound to occur while delivering vaccines at breakneck speed during a pandemic that we absolutely had to buy ample insurance. It's no use blaming the tree you ran into in an uninsured car. The fact that the bad luck *mattered* is ultimately on the government.

19 Quoted in Xiao (2021).

20 Australia Covid vaccine tracker by source, COVIDLIVE, https://covidlive.com.au/report/vaccinations-source

It is tempting to think that the absence of economic thinking was the product of the absence of economists in the room at the time these crucial decisions were made. Was this just a case of a demarcation dispute between the departments of Health and Treasury? This is what we had assumed, but it has since been confirmed to us by multiple sources that Treasury was absolutely in the room when these crucial decisions were made. This raises the question of why Treasury failed to speak up.

Another key failure of the vaccine procurement strategy is common to many other large public procurements in Australia: the irresistible temptation of a bit of industry policy. The two horses that the Australian government put almost all its money on were, in one way or another, home-grown. First, the UQ-developed vaccine, which would come to fail, had been intended to be produced by CSL in Victoria. Second, the British-developed AstraZeneca vaccine was also capable of being made under licence by CSL, and indeed would come to be so. It is simply undeniable, based on the format of Australia's initial vaccine procurement plan, that domestic manufacturing capability was the government's number-one priority. Australia had no domestic mRNA manufacturing capability, and so we ordered little-to-no mRNA vaccines. The UQ and AstraZeneca vaccines could be produced in Victoria, and so that's what we ordered.

On 12 February 2021, Scott Morrison donned a hairnet and his trademark Australian-flag face mask and toured CSL's manufacturing facilities with Greg Hunt, a gaggle of press photographers in tow. In an uncharacteristic act of speed and decisiveness, the TGA approved local manufacture by CSL little more than a month later, on 21 March 2021 — just five days after approving the overseas-manufactured version of AstraZeneca (DHAC, 2021c). Two CSL sites in Melbourne were involved, with the CSL Behring site in Broadmeadows manufacturing the active raw ingredients for the vaccine, and Sequiris in Parkville manufacturing the final vaccine, filling vials and packaging them.

There is absolutely some good sense in investing in a domestic manufacturing capability. In fact, it was possibly the sole example of sound risk management in the whole vaccine rollout. Global supply chains were being stretched logistically during the pandemic. There was a legitimate risk that Australia would not be able to get contracted for doses of vaccines that were being manufactured in the Northern Hemisphere. On top of that, there were serious concerns about so-called "vaccine nationalism."

In the first week of March 2021, Italy blocked the export of a quarter of a million doses of the AstraZeneca vaccine that Australia had contracted for. Italian Foreign Minister Luigi Di Maio made the surreal argument that Australia had a comparatively low infection rate and so Europe needed to be prioritised, contract be damned. He said: "As long as these delays remain, it is right for the countries of the European Union to block exports toward nations that are 'not vulnerable' as a response to the failure of companies to respect commitments." And French Health Minister Olivier Véran seemed to concur: "I understand [Italy's view]. We could do the same thing." (Hamilton & Holden, 2021b).

The risks were real. Having a domestic manufacturing capability was a means of buying an insurance policy against exactly this kind of behaviour. But it needn't have been a case of either/or. Developing a domestic manufacturing capability did not in any way preclude the government from also buying insurance — in the form of redundant mRNA orders — against other possibilities, such as the domestically produced AstraZeneca vaccine running into trouble (as it did). Ultimately, the government needed to buy insurance against a whole raft of unforeseen events.

A much less sound motivation was the notion that manufacturing AstraZeneca in Australia could also provide a boost to CSL and the Australian economy. This could be a way of killing two economic birds with one proverbial policy stone. Added to that was the appeal of the UQ vaccine which, ultimately, turned out to be unviable as it caused false-positive HIV test results. While it would have been a great story to have had an Australian-developed vaccine, and it was a good insurance policy to have a domestic manufacturing capability, the federal government was clearly overly taken with these possibilities. It had one job: getting Australians vaccinated so the country could reopen. That ought to have been the federal government's number-one priority. It would turn out to be one hell of an own-goal to back Aussie jobs by favouring domestically produced vaccines, when doing so would end up delaying the vaccine rollout at a cost of more than $50 billion to the Australian economy. And, in the end, the vast majority of administered doses would come from abroad anyway.

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The Big Thaw: who governs Antarctica's ice?

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Introduction

The Antarctic continent covers an area of around 14 million km^2, with almost all of its surface covered by ice sheets. At the littoral edge of the continent, there are large ice shelves that extend seawards — in some cases by many hundreds of kilometres. Further seawards lies an expanse of sea ice that grows in winter and contracts in summer.

Antarctica, like all places on Earth, is being transformed by human activities.[2] The volume and area of Antarctica's ice are declining, with flow-on effects for Antarctic ecosystems, for regional and global climate systems, and for sea level rise. Australia has a special interest in preserving Antarctica, not only because of what it means for the Australian Antarctic Territory, but also because changes both to Antarctica's ice cover and to deep ocean currents in the Southern Ocean influence temperature and rainfall patterns in Australia, affecting communities, ecosystems and agriculture.

As early as 1989, the parties to the Antarctic Treaty adopted a resolution which expressed an awareness of "the role that Antarctica and the Southern Ocean play in interactive physical, chemical and biological processes that regulate the total Earth System," recognised that "the Antarctic region has a high negative radiation budget and so acts as one of the Earth's 'refrigerators'," noted that "the Antarctic ice sheet contains enough water to raise global sea level world-wide some 60 metres," and warned that "warming which makes even a small change to this volume of ice will have a significant impact on sea level."[3] Thanks to scientific advances in the decades that have followed, we now have a clearer understanding of what is happening to Antarctica and how sensitive it is to rising temperatures.

We can agree it is important that we pay attention to Antarctica's ice, and hold on to as much of it as we can. But how can this be achieved? How is Antarctica's ice governed?

Governing Antarctica

Before addressing these questions, it is necessary to introduce the unique set of legal arrangements for Antarctica. Historian David Day describes Antarctica as "a mirror

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2 See generally Meredith MP, Melbourne-Thomas J, Naveira Garabato AC and Raphael M (eds) (2025) *Antarctica and the Earth System*. London: Routledge. https://doi.org/10.4324/9781003406471

3 Antarctic Treaty Consultative Meeting (1989) *Recommendation XV-14: Promotion of International Scientific Cooperation*. ATCM XV, Paris. Available at: https://www.ats.aq/devAS/Meetings/Measure/183 (Accessed 10 July 2025).

on which centuries of human hopes, fears and desires have been projected."[4] These projections have taken a myriad of legal forms. In the early twentieth century, seven states made claims to Antarctica: Argentina, Australia, Chile, France, New Zealand, Norway and the United Kingdom. These resulted in most of the continent coming under sovereignty claims. It was a former President of the Royal Society of NSW, Sir Edgeworth David, leader of the first expedition to reach the South Magnetic Pole in 1909, who played a central role with Sir Douglas Mawson, in establishing Australia's claim alongside Douglas Mawson. Australia's Antarctic claim remains the largest, bringing approximately 42 per cent of the continent within the Australian Antarctic Territory. Australia's claim is not widely recognised by other governments, but the absence of express recognition does not undermine the objective legal basis for Australia's Antarctic possessions.[5]

In the middle of the twentieth century there was to be a decisive change in Antarctica's international legal treatment, from being a domain of territorial designs to becoming an object of international concern and management. This was achieved in the Antarctic Treaty,[6] signed in Washington DC in 1959 by the seven claimants and five other countries[7] active during the International Geophysical Year of 1957–58. The very first meeting of the Antarctic Treaty parties took place in Old Parliament House, Canberra in 1961.

Several factors, including scientific fascination with Antarctica, explain this shift from competition to cooperation. However, the main driver was the Cold War superpower antagonism. There were very real fears that Antarctica would be a new front in the nuclear standoff between the United States and the Soviet Union.[8] And so the Antarctic Treaty's preamble declares that "it is in the interest of all [hu]mankind that Antarctica shall continue forever to be used exclusively for peaceful purposes and shall not become the scene or object of international discord."

To give effect to this goal the Treaty has three main elements. First, it provides that Antarctica is to be used exclusively for peaceful purposes and prohibits the deployment of military forces in Antarctica, except for scientific research or other peaceful uses. It also prohibits nuclear explosions in Antarctica and the disposal of radioactive wastes. In addressing the risks associated with nuclear weapons and waste, the Antarctic Treaty was a response to one of the defining technologies of the Anthropocene, the human-dominated period in Earth history which we now inhabit.[9]

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4 Day D (2012) Ice works: Three portraits of Antarctica. *The Monthly*, March, p. 56. See Day D (2013) *Antarctica: A Biography*. Sydney: Vintage.

5 Scott SV (2021) The irrelevance of non-recognition to Australia's Antarctic territory title. *International and Comparative Law Quarterly* 70(2): 491–503.

6 Signed at Washington, D.C., 1 December 1959. United Nations Treaty Series, vol. 402, p. 71.

7 Belgium, Japan, South Africa, Soviet Union and the United States.

8 Dodds K (2017) Antarctic Geopolitics. In: Dodds K, Roberts P and Hemmings AD (eds) *Handbook on the Politics of Antarctica*. Cheltenham: Edward Elgar Publishing, pp. 199–214, p. 205.

9 While not recognised as a formal geological interval, the 'Anthropocene' is described by the International Union of Geological Sciences as an 'invaluable descriptor of human-environment interactions' in 'discussions

Second, the Antarctic Treaty promotes the freedom of scientific investigation, and requires states to co-operate to the greatest extent possible in research endeavours. The Antarctic Treaty has made a major contribution to understanding global challenges, including ozone depletion and climate change, thanks to the central place that science occupies in Antarctic governance. As environmental anthropologist Jessica O'Reilly has observed, Antarctica is less a *terra nullius* or *terra incognita*, and instead is more a *terra clima* in constituting both a barometer of climate change and also as one of the key "geographic epicentres of climate science."[10] Illustrating this is the central place that climate science plays in the Antarctic science programs of Australia[11] and other Antarctic states.

Third, and most importantly, the Antarctic Treaty includes a carefully drafted provision on sovereignty. To employ an overused metaphor, this provision freezes sovereign claims for the life of the treaty. It provides that existing territorial claims are neither recognised nor rejected, while no new claims or the enlargement of existing claims is permitted. It is this delicate compromise that is central to the stability of the Antarctic Treaty, allowing parties to manage Antarctic affairs without having to defend or protest territorial interests.

Another consequence of the suspension of sovereignty is that claimant states cannot exercise their usual jurisdiction over the territories they claim. So in the Australian Antarctic Territory, and indeed anywhere in Antarctica, the Australian Government will extend Australian law to Australian nationals.[12] The government, however, will not apply Australian law to non-nationals, including in the Australian Antarctic Territory, such as Japanese whalers who operated around Antarctica from the 1980s. Japanese so-called scientific whaling offshore Australia's Antarctic Territory was brought to an end by Australia through successful litigation in the International Court of Justice[13] on the basis of breaches of the 1946 International Convention for the Regulation of Whaling,[14] not through the enforcement of national jurisdiction.

A central feature of the Antarctic Treaty was that it established an evolving legal regime. The Treaty laid the legal foundations for what was to become the Antarctic

of the anthropogenic impacts on Earth's climatic and environmental systems.': International Union of Geological Sciences (2024) *The Anthropocene: IUGS-ICS Statement (Extended)*. IUGS. Available at: https://www.iugs.org/post/the-anthropocene-iugs-ics-statement (Accessed 15 July 2025).

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12 Stephens T and Boer B (2007) Enforcement and compliance in the Australian Antarctic Territory: Legal and policy dilemmas. In: Kriwoken LK, Jabour J and Hemmings AD (eds) *Looking South: Australia's Antarctic Agenda*. Australia: Federation Press, pp. 54–70.

13 *Whaling in the Antarctic (Australia v. Japan: New Zealand intervening)*, Judgment of 31 March 2014, I.C.J. Reports 2014, p. 226.

14 *International Convention for the Regulation of Whaling*, Washington, 2 December 1946. United Nations Treaty Series, vol. 161, p. 72.

Treaty System, a collection of treaties and other instruments for governing Antarctica. It is through this process that Antarctica has gained new elements, such as the 1980 Convention on the Conservation of Antarctic Marine Living Resources[15] to protect Antarctic fisheries, and even an Antarctic emblem. It is now one of the world's most comprehensive international legal arrangements.[16] As Don Rothwell has observed, the Antarctic Treaty System stands apart as one of the world's most durable and resilient legal regimes.[17]

One fascinating aspect of the regime is the pivotal role that scientists have played in constructing the Antarctic Treaty System. As Alessandro Antonello explains, after the Antarctic Treaty was agreed, "a group of states and their diplomats and officials, scientists, and scientific institutions transformed the Antarctic from a cold, abiotic, and sterile wilderness, a lifeless and inert stage for geopolitical competition, into a fragile environment and ecosystem demanding international protection and management."[18] The key moment in this transformation came in the late 1980s when the mining question was confronted and resolved. The Antarctic Treaty did not deal with the issue, and it was not clear on what legal basis mining in the Antarctic could take place. To resolve the uncertainty, the 1988 Convention on the Regulation of Antarctic Mineral Resources[19] (Minerals Convention) was adopted in Wellington, New Zealand, to permit mining under strict conditions.

However, when the environmental implications of Antarctic mining were understood by publics in a number of states there was a quick turn-around in international attitudes. Australia and France reversed their support for the Minerals Convention and pushed instead for a comprehensive treaty to protect the Antarctic environment. The diplomatic effort was led by French Prime Minister Michel Rocard and Australian Prime Minister Bob Hawke.[20] This resulted, in a short time, in the effective abandonment of the Minerals Convention, which never entered into force, and the adoption of the 1991 Environmental Protocol.[21] The Environmental Protocol not only established an indefinite mining ban,[22] but the

15 *Convention on the Conservation of Antarctic Marine Living Resources*, Canberra, 20 May 1980. United Nations Treaty Series, vol. 1329, p. 47.

16 See further Saul B and Stephens T (2015) *Antarctica in International Law*. Oxford: Hart Publishing.

17 Rothwell D (2021) The Antarctic Treaty at sixty years: past, present and future. *Melbourne Journal of International Law* 22(2): 1–25.

18 Antonello A (2019) *The Greening of Antarctica: Assembling an International Environment*. Oxford: Oxford University Press, p. 4.

19 Convention on the Regulation of Antarctic Mineral Resource Activities (1988). Concluded at Wellington, New Zealand, 2 June 1988. Not in force. Depositary: Government of New Zealand.

20 See generally Jackson A (2021) *Who Saved Antarctica? The Heroic Era of Antarctic Diplomacy*. Cham: Palgrave Macmillan, ch. 6.

21 Protocol on Environmental Protection to the Antarctic Treaty, Madrid, 4 October 1991. United Nations Treaty Series, vol. 2941, No. 5778.

22 Resolution 6 (2016) — ATCM XXXIX — CEP XIX, Santiago: Confirming ongoing commitment to the prohibition on Antarctic mineral resource activities, other than for scientific research. Available at: https://www.ats.aq/devAS/Meetings/Measure/642 (Accessed: 15 July 2025).

parties also committed themselves to the comprehensive protection of the Antarctic environment, and designated Antarctica as a natural reserve, devoted to peace and science.

The conversion of the Antarctic regime from a relatively narrow, sovereignty- and science-focused regime to one concerned with comprehensive environmental protection goals was not inevitable. It was the outcome of the efforts of scientists and other actors to open new possibilities for perceiving the continent and the Antarctic Treaty's foundational principles. The abandonment of the Minerals Convention and the adoption of the Environmental Protocol also served to allay suspicions of Asian and developing states that western powers were seeking to arrogate the continent and its resources to themselves. The Antarctic Treaty now has 58 parties, 29 of which have "consultative" status to make decisions about the continent at Antarctic Treaty Consultative Meetings.[23] The Environmental Protocol also established the Committee on Environmental Protection, a central forum for the governance of Antarctic environmental matters.

Over time the agenda of these meetings has become very full, dealing with issues ranging from Antarctic heritage sites, to environmental impact assessment of Antarctic aerodromes, to Antarctic tourism. I have had the privilege of an attending a consultative meeting, as an academic observer with the Australian Government Delegation, and have seen first-hand the professionalism and commitment of Australia's diplomats and scientists.

Governing the ice

So we now know how Antarctica is governed in a general sense, and can turn to examine how the world's ice and snow (known collectively as the *cryosphere*) is governed, including in Antarctica.

In 1959 the United States constructed Camp Century under the Greenland Ice Sheet with the hope of deploying nuclear ballistic missiles there. Despite its centennial ambitions, Camp Century was abandoned within a decade. Yet the base was never decommissioned, as it was assumed that the facility's hazardous contents would remain forever entombed. This turned out to be a dangerous assumption. Glaciologists have discovered that with the Greenland Ice Sheet melting, Camp Century and its radiological wastes are now being released from their icy clutches.[24] Greenland's ice sheet is melting much faster than previously estimated,[25] adding freshwater that slows down the Atlantic's circulation.[26]

23 The consultative parties comprise the 12 original parties together with 17 subsequent parties that have demonstrated interest in Antarctica by conducting substantial scientific research activity there: Antarctic Treaty, Art. 9(2). See Hughes KA, Gray AD and Ager BJ (2024) 'Attainment of consultative status by parties to the Antarctic Treaty: past, present and future', *The Polar Journal* 14(2): 560–591.

24 Colgan W, Dethloff K, Fettweis X et al. (2016) The abandoned ice sheet base at Camp Century, Greenland, in a warming climate. *Geophysical Research Letters* 43(12).

25 Greene CA, Gardner AS, Wood M et al. (2024) Ubiquitous acceleration in Greenland Ice Sheet calving from 1985 to 2022. *Nature* 625: 523–528.

26 Pontes GM and Menviel L (2024) Weakening of the Atlantic Meridional Overturning Circulation driven by subarctic freshening since the mid-twentieth century. *Nature Geoscience* 17: 1291–1298. https://doi.org/10.1038/s41561-024-01568-1

Furthermore, the Arctic's summer sea ice is disappearing before our eyes.[27]

There is a strong sense across the Arctic that the Anthropocene has arrived, with Indigenous communities at the front lines of this change. Arctic researchers have been posing and answering research questions in response to this reality for some time; it was over a decade ago that the United States National Academy of Science released a book-length report on "The Arctic in the Anthropocene."[28] At the other pole there has been a belief, or wish, or hope, that Antarctica is more resistant to change. Perhaps Antarctica is the place that this new era has overlooked? However, the ice is telling a different story.

There are three main types of ice in Antarctica — the ice sheets, the ice shelves (land ice that flows out over the coastal ocean), and surrounding floating sea ice. Let us begin with the latter first and then move landwards. There is considerable natural variation in Antarctic sea ice extent,[29] although the recent and abrupt retraction is concerning. The average Antarctic sea ice extent for July 2024 was 11% below the 1991–2020 average.[30] This was the second-lowest extent for July, and 2024 was the third year in a row characterised by a relatively large negative anomaly. This indicates that a "regime shift" may be underway, with sea ice pushed to a new state of diminished coverage similar to that in the Arctic, from which it may not recover. Australian Antarctic Division sea-ice scientist Dr Petra Heil has highlighted the wide-ranging effects this is having on "the climate and ecosystems, both nearby and further afield, including at lower latitudes, which are home to the majority of the human population and their economic interests."[31]

More troubling still is the melting of Antarctic ice shelves and ice sheets, as it involves change of sufficient scale to transform both the continent and the planet. Antarctica's ice is not a fixed feature of the landscape; it is a dynamic system that has been in equilibrium for thousands of years. That balance is changing as temperatures rise, and the ice is assailed from warm air from above and warm waters from below. In 2025, surface melting on the Antarctic ice sheet set a record for the satellite observation period.[32]

Research by glaciologist Rob DeConto and others suggests that Antarctic ice sheets

27 NASA Earth Observatory (2024) *Arctic and Antarctic sea ice approached historic lows*. Available at: https://earthobservatory.nasa.gov/images/153457/arctic-and-antarctic-sea-ice-approached-historic-lows (Accessed 15 July 2025).

28 National Research Council (2014) *The Arctic in the Anthropocene: Emerging Research Questions*. Washington, D.C.: The National Academies Press. Available at: https://nap.nationalacademies.org/catalog/18726/the-arctic-in-the-anthropocene-emerging-research-questions (Accessed 11 July 2025)

29 Matear RJ, Oke PR, Risbey JS et al. (2015) Sources of heterogeneous variability and trends in Antarctic sea-ice. *Nature Communications* 6: Article 8656.

30 National Snow and Ice Data Center (NSIDC) (2024) 2024 Antarctic sea ice maximum extent finishes at second lowest. Available at: https://nsidc.org/sea-ice-today/analyses/2024-antarctic-sea-ice-maximum-extent-finishes-second-lowest (Accessed 11 July 2025)

31 Australian Antarctic Division (2024) *Antarctic sea ice in crisis*. Available at: https://www.antarctica.gov.au/news/explore-antarctica/antarctic-sea-ice-in-crisis/ (Accessed 11 July 2025)

32 National Snow and Ice Data Center (NSIDC) (2025) The Great Un-Freezing: Record Antarctic surface melt extent set; Peninsula melting slows. Available at: https://nsidc.org/ice-sheets-today/analyses/great-un-freezing-record-antarctic-surface-melt-extent-set-peninsula-melting-slows (Accessed 11 July 2025).

are far less stable than generally thought.[33] The last time CO_2 concentrations were as high as they are today was during the Pliocene, three million years ago, in which the sea level was 10–30 metres higher, there was no West Antarctic Ice Sheet, and the East Antarctic Ice Sheet was in retreat. As glaciologist Knut Christianson has commented in relation to the Thwaites Glacier in West Antarctica, "[w]e like to think that change happens slowly, especially in a landscape like Antarctica … [b]ut we now know that is wrong."[34]

Continued growth in concentrations of CO_2 in the atmosphere will eventually trigger the collapse of Antarctica's ice, as the buttressing shelves melt and the sheets then slide into the sea in much the same way as a ship is launched down a slipway. DeConto has described this process as "literally remapping how the planet looks from space."[35] The good news is that substantial ice mass loss may be avoided if greenhouse-gas emissions are reduced sufficiently to limit the average global temperature rise to about 2 °C.[36] This happens to be upper temperature goal of the 2015 Paris Agreement on Climate Change,[37] the most recent and significant treaty adopted under the 1992 United Nations Framework Convention on Climate Change (UNFCCC).[38]

To date, we have mostly imagined humanity's physical power over Antarctica, with states projecting an abstract authority through exploration, map-making, nationalist claims and gestures, and the passing of myriad Antarctic laws, many of which have little more than symbolic effect. However, in the Anthropocene the future of Antarctica is now in human hands, with the fate of its mass of ice and snow determined from afar by human-induced changes to the global climate. We have therefore collapsed the separation between global human activities and their impact on Antarctica.

While the Antarctic Treaty System has been effective in enabling the detection and anticipation of state change in Antarctica, principally by rendering Antarctica a *terra clima*, ironically it has shown reluctance to confront implications of the big thaw. As Antonello puts it, "[i]ce still has not become a central diplomatic concern of the Antarctic Treaty parties," despite the efforts of civil society groups and scientists.[39] Governments have sought refuge in science, responding to the climate threat by intoning the refrain that climate impacts on the continent need

33 DeConto RM and Pollard D (2016) Contribution of Antarctica to past and future sea-level rise. *Nature* 531: 591–597; Aitken ARA, Roberts JL, van Ommen TD et al. (2016) Repeated large-scale retreat and advance of Totten Glacier indicated by inland bed erosion. *Nature* 533: 385–389.

34 Goodell J (2017) The doomsday glacier. *Rolling Stone*, 10 May. Available at: http://www.rollingstone.com/politics/features/the-doomsday-glacier-w481260 (Accessed 10 July 2025)

35 Tollefson J (2016) Antarctic model raises prospect of unstoppable ice collapse. *Nature* 531: 562–563.

36 Stokes CR, Abram NJ, Bentley MJ et al. (2022) Response of the East Antarctic Ice Sheet to past and future climate change. *Nature* 608: 275–286.

37 Paris Agreement on Climate Change, Paris, 12 December 2015. United Nations Treaty Series, vol. 3156, p. 79.

38 United Nations Framework Convention on Climate Change, New York, 9 May 1992. *United Nations Treaty Series*, vol. 1771, p. 107.

39 Antonello A (2019) *The Greening of Antarctica: Assembling an International Environment*. Oxford: Oxford University Press, p. 173. A key civil society organisation in this arena is the Antarctic and Southern Ocean Coalition, https://www.asoc.org/ (Accessed 15 July 2025).

to be understood better if Antarctica is to be protected, but leaving unsaid how this protection is to occur and who will have responsibility for achieving it. This is understandable. The Antarctic regime has an ingrained culture of exceptionalism; at times it has operated as an exclusive club of nations. There is also the reality that climate change cannot be directly addressed within the Antarctic Treaty System, and necessarily requires action through global forums, principally the 2015 Paris Agreement on Climate Change.

The fundamental challenge, as veteran Australian Antarctic diplomat Andrew Jackson observes, is that "the greatest risk to Antarctica's environment comes from events outside the Treaty area, rather than within," and therefore beyond the apparent purview of the Antarctic Treaty System.[40] The Antarctic Treaty System cannot by itself govern Antarctica's ice, and so it is through the Paris Agreement that states are seeking to avoid dangerous climate change, and all that comes with it, including the melting of the cryosphere. The Paris Agreement was adopted in 2015 and is intended to put the world on the path to carbon neutrality. However, as the United Nations Environment Programme reports, there remains a sizeable gap between the goals of the agreement and global emissions,[41] which reached a record high in 2024.[42]

The links between the Paris Agreement goals and the Antarctic environment are not widely understood, including by the parties to the Paris Agreement itself, despite the efforts of climate scientists, such as paleoclimatologist Tim Naish, who delivered the Scientific Committee on Antarctic Research lecture at the 40th Antarctic Treaty Consultative Meeting. Naish highlighted the links between the Paris Agreement and the Antarctic environment. He explained that the "threshold for loss of Antarctica's stabilizing ice shelves may be the Paris target of 2 °C of global warming. Go above it and you commit the planet Earth to multi-metre sea-level rise that may be irreversible for millennia."[43] Naish noted that we are now at a critical moment, and time to act is short. He argued that despite the significant impacts of climate change on "Antarctic activities and operations … the ATS does not have a coherent voice under the Paris Agreement" and made a number of suggestions for greater engagement by the Antarctic Treaty System with the UNFCCC and the Paris Agreement.

We are at a critical point of potential disruption of the existing Antarctic order, with environmental change causing more serious and permanent harm to physical and living components of the Antarctic ecosystem than mining or tourism or any activity on the continent ever could. There are at least

40 Jackson A (2021) *Who Saved Antarctica? The Heroic Era of Antarctic Diplomacy*. Cham: Palgrave Macmillan, pp. 366–367.

41 United Nations Environment Programme (UNEP) (2024) *Executive summary*. In: *Emissions Gap Report 2024: No more hot air … please! With a massive gap between rhetoric and reality, countries draft new climate commitments*. Nairobi: UNEP. Available at: https://doi.org/10.59117/20.500.11822/46404 (Accessed 11 July 2025).

42 International Energy Agency (IEA) (2025) Global Energy Review 2025: CO_2 emissions. Available at: https://www.iea.org/reports/global-energy-review-2025/co2-emissions (Accessed 11 July 2025).

43 Naish T (2017) What does the United Nations Paris Climate Agreement mean for Antarctica? *Antarctic* 35(4): 46–51.

two plausible scenarios in how the Antarctic Treaty System will respond to the "big thaw." One is that the Antarctic environment is radically transformed (e.g. the complete loss of sea ice, with all the implications that carries for the whole Southern Ocean ecosystem[44]) such that the regime loses its key environmental protection rationale, in which case dormant tensions over access, resources, and even sovereignty could be reanimated. If the Antarctic environment is altered to such an extent that all, or the majority of, existing environmental protection measures become ineffective, then new measures become largely without object. Once this occurs, the rationale for controlling or prohibiting various activities on the continent could be challenged, and disputes over access to resources could resurface.

Antarctic biologist Steven Chown notes that "[s]igns of discord in the ATS bodies are … already visible, such as the inability of parties to [the Convention on the Conservation of Antarctic Marine Living Resources] to agree on further marine protected areas."[45] Among a small number of parties to this Convention, there has been significant backlash against centring climate-related concerns in the regime, and several states are now blocking all new conservation measures.[46] There is a possibility that parties to the Antarctic Treaty, including potentially even the United States, will abandon an interest in Antarctic science and conservation for other reasons, including domestic political considerations,[47] or renewed geostrategic tensions.

A second, more optimistic, scenario, sees a concerted effort to centre environmental concerns in Antarctic governance, in a manner analogous to the mining debate, to build consensus within the Antarctic Treaty System and reinforce global support for the regime. Under this scenario, Antarctica again becomes a centre of global environmental attention — as a kind of "Ark" — consistent with the "last wilderness" narratives that have been dominant in Antarctic discourses. The Antarctic Treaty System is imbued with the romantic environmentalism of wilderness, even if this narrative oversimplifies the legal reality. Elizabeth Leane has explained in her work on representations of the South Pole that the notion of Antarctica as a pristine wilderness, indeed the "last wilderness," "last refuge" and "last hope," has been central to depictions of the continent since the rise of global environmental consciousness in the 1980s.[48]

Rather than the Antarctic Treaty System becoming fragmented, it could thereby become the voice of Antarctic protection

44 Silvano A (2025) Completely unexpected: Antarctic sea ice may be in terminal decline due to rising Southern Ocean salinity. *The Conversation*, 30 June 2025. Available at: https://theconversation.com/completely-unexpected-antarctic-sea-ice-may-be-in-terminal-decline-due-to-rising-southern-ocean-salinity-259743 (Accessed 15 July 2025).

45 Chown SL (2017) Antarctic environmental challenges in a global context. In: Dodds K, Hemmings AD and Roberts P (eds) *Handbook on the Politics of Antarctica*. Cheltenham, UK: Edward Elgar, pp. 523–539.

46 Barraclough A (2024) *Russia and China block every proposal at Antarctic marine life conservation conference in Hobart*. ABC News. Available at: https://www.abc.net.au/news/2024-10-28/russia-china-block-proposals-antarctic-marine-life-conservation/104523490 (Accessed 15 July 2025).

47 Press T and Goldsworthy L (2025) As Donald Trump cuts funding to Antarctica, will the US be forced off the icy continent?. *The Conversation*, 11 May 2025. Available at: https://theconversation.com/as-donald-trump-cuts-funding-to-antarctica-will-the-us-be-forced-off-the-icy-continent-254786 (Accessed 15 July 2025).

48 Leane E (2016) *South Pole: Nature and Culture*. London: Reaktion Books.

to a global audience. The Antarctic Treaty parties could, through a Resolution or series of Resolutions, make a contribution to governing the cryosphere by affirming the importance of retaining Antarctica's ice shelves and sheets, and by noting the CO_2 concentrations and temperature tipping points at which they will begin an irreversible collapse.[49] In practical terms, this could occur through dialogue with the annual climate conferences. Just such a proposal was made by Australia in 2012 at the 35th Antarctic Treaty Consultative Meeting, with the possibility mooted that the Antarctic Treaty Secretariat could become an observer organisation to UNFCCC.[50] However, the suggestion was not adopted at the meeting and has not been progressed since. Accordingly, the Antarctic Treaty System remains largely disconnected from the global climate regime. This is in sharp contrast to the Arctic Council, which has been heavily engaged in global climate diplomacy.[51] The effect of this is that there remains a substantial governance gap when it comes to the preservation of Antarctica's ice — it is not a central concern of either the Antarctic Treaty System or the UNFCCC.

While it is too early to ascertain which of the two suggested scenarios (or another scenario) the Antarctic Treaty System is heading towards there are some hopeful signs. At the 2023 Antarctic Treaty Consultative Meeting, the Antarctic Treaty parties adopted the Helsinki Declaration on Climate Change and the Antarctic[52] which, for the first time in decades, foregrounded the importance of the Antarctic for the Earth system and its cryosphere. The Declaration opened by "[r]eaffirming [the] firm commitment [of the parties] to combat the adverse impacts of climate change" and proceeded, in a lengthy preamble, to recognise the "critical role" of Antarctica and the Southern Ocean for the global climate. It went on to express "deep concern" that "further irreversible change is likely to occur without accelerated efforts to reduce greenhouse gas emissions" in line with the Paris Agreement, including the "multiple metres of sea level rise resulting from ice-sheet loss that is irreversible for centuries to millennia [and] would have devastating to catastrophic impacts, particularly on millions of people living in low elevation coastal zones." The parties also noted the "tools … at their disposal for action, such as research, monitoring management, environmental protection, advocacy and communication."

The operative paragraphs also included several interesting and note-worthy departures from the past reticence of the parties. There is a commitment to "substantially increasing … efforts to communicate the global implications of climate change in Antarctica within our own countries and in international

49 See further Stephens T (2020) Governing Antarctica in the Anthropocene. In: Leane E and McGee J (eds) *Anthropocene Antarctica*. Abingdon, UK: Routledge, pp. 17–32.

50 Commonwealth of Australia (2012) *ATCM interests in international climate change discussions — options for enhanced engagement*. Working Paper 32, ATCM XXXV, CEP XV, Hobart.

51 Although the Council's work has been severely impeded following Russia's invasion of Ukraine: Andreeva S and Rottem SV (2024) How and why the Arctic Council survived until now — an analysis of the transition in chairship between Russia and Norway. *The Polar Journal* 14(1): 229–246.

52 Antarctic Treaty Consultative Meeting (2023) *Resolution 2 (2023): Helsinki Declaration on Climate Change and the Antarctic*. ATCM XLV. Available at: https://documents.ats.aq/ATCM45/ad/atcm45_ad006_e.pdf (Accessed 15 July 2025).

forums, and the need to prevent the irreversible changes to Antarctica and consequential implications for the planet." Notably, the Helsinki Declaration specifically emphasised the climate significance of mining ban under Article 7 of the Environmental Protocol, by noting that this includes a prohibition on the extraction of fossil fuels. These more novel elements sit alongside familiar regime responses, including encouraging all states and operators in Antarctica to reduce their carbon footprint, and inviting the Scientific Committee on Antarctic Research to continue providing annual climate reports to the parties. Climate change was also a prominent issue on multiple agenda items at the 2024 and 2025 Antarctic Treaty Consultative Meetings, with the parties "highlight[ing] the need to continue collectively making progression on advancing the goals set in the [Helsinki Declaration]."[53]

Conclusion

Antarctica's ice is governed in formal terms by two regimes: the Antarctic Treaty System and the global climate regime under the UNFCCC and Paris Agreement. However, both have to date shown a marked reluctance to confront directly the challenge of maintaining the stability of Antarctica's ice cover and mass. The current preoccupations of the Antarctic Treaty System are with localised environmental impacts, such as stationing, expeditions, research, fishing, and tourism. It is almost as if the hyper-environmental focus of Antarctic regional governance is a coping strategy, a fixation being pursued to compensate for the regional and global failure to address the larger and more serious threat.

There is therefore currently no straightforward answer to the question as to who governs Antarctica's ice. While the Antarctic Treaty System has brought attention to the issue since 1989, this has not progressed beyond the identification of the scale of the problem via increasingly sophisticated climate science research, made possible by this unique legal regime that has prioritised science in Antarctic diplomacy. Antarctica has become one of the most important sites of climate research globally, yet the Antarctic Treaty System itself has not been a central forum for governance of the cryosphere. The 2023 Helsinki Declaration signalled that a more proactive approach is required; however, in order for this to occur, there will need to be concerted effort by like-minded parties to elevate Antarctica's "big thaw" on the international agenda, in a manner akin to the Antarctic minerals debate in the late 1980s and early 1990s. This is difficult to achieve in the current unstable geopolitical context,[54] one in which several parties to the Antarctic Treaty have shown uninterest or even hostility towards mainstreaming climate concerns in Antarctic governance.

53 Antarctic Treaty Consultative Meeting (2024) *Final Report of the Forty-Sixth Antarctic Treaty Consultative Meeting*, p. 68. ATCM XLVI. Available at: https://documents.ats.aq/ATCM46/fr/ATCM46_fr001_e.pdf (Accessed 15 July 2025).

54 See generally McGee J, Edmiston D and Haward M (2022) *The Future of Antarctica: Scenarios from Classical Geopolitics*. Singapore: Springer.

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Mozart's secular trinity

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Abstract

This article examines the second movement of Mozart's Piano Sonata No. 2 in F, KV 280[1] and shows how the number 3 manifests itself on multiple levels in the movement, ranging from the most fundamental interval of harmonic progression to melodic motifs on the surface. The symbolic significance of the number 3 is considered in light of Mozart's religious upbringing.

Introduction

In this paper I examine the role of three-part structures in the second movement of Mozart's Piano Sonata No. 2 in F, KV 280.[2] This movement is written in "sonata-exposition" form, which comprises three parts: Exposition, Development and Recapitulation. It is written in the key of F minor, which is the home or tonic key. The number 3 is significant as a musical concept in secular Western music owing to its symbolising the Holy Trinity.

Exposition (bars 1–24)

The Exposition opens with the first subject in the tonic. In terms of texture, the Exposition divides into three discrete parts. Part 1, comprising the first eight bars, emphasises two musical figures or motifs: the first, a dotted-quaver figure (bar 1, in the right hand); and the second, a figure consisting of regular quavers (bar 2, in the right hand). The progression of motifs from one bar to the next is elegant, evoking the grace and adroitness of a skilled dancer.

Part 2, bars 9 to 20, is distinguished by an "Alberti bass," which comprises continuous semiquavers. This motif opens on A♭. This may suggest that A♭ is to be the new tonic key, a logical modulation for a piece set in F minor, as it is the "relative major" key. However, it is only an anticipation of the later modulation at this point as the left hand outlines a triad, a chord of three notes comprising two intervals of a third, in the weak form of the second inversion of A♭ (E♭, A♭, C).

Bar 14 announces a key stage of the harmonic journey in the movement by stating E♭, the dominant of A♭. While the E♭ triad (E♭, G, B♭) has sounded more than once commencing in bar 9, in bar 14 it stands out for the right hand's outlining of its second and third notes in a higher register. The second subject, in the key of A♭, is reached in bar 17. While the Alberti bass continues, a new motif consisting of a pair of repeated quavers is heard in the right hand. Part 2 thus yields a three-part division: (i) bar 9; (ii) bar 14; (iii) bar 17.

In Part 3, bars 21 to 24, the harmonic progression from bar 21 (second chord) through to bar 22 (penultimate chord) is repeated at

1 See the Digital Mozart Edition, at https://dme.mozarteum.at/en/ [Ed.]

2 The score is available online. https://dme.mozarteum.at/DME/nma/nmapub_srch.php?l=2. A video with score of the Sonata, with the second movement starting at 4:27, is available on YouTube. https://youtu.be/vLRslNG6TPE.

the lower octave, giving rise to a bipartite division.

Part 1 offers abundant examples of quaver figures outlining the interval of a third in the right hand. As an example, observe the second figure in bar 2. In bar 3, the second figure not only outlines the interval of a third but comprises vertical intervals of thirds. In Part 2, the interval of a third defines linear relations between longer notes in the right hand part. Bars 14 to 15 offer two examples.

Development (bars 25–36)

The Development contains a crystal-clear division into three parts. Part 1, bars 25 to 28, recalls the first subject from the Exposition in bar 1. The specific harmonic progression, however, is different. Part 1 of the Development opens on A♭, the relative major key, and closes into B♭, the subdominant of F minor. Part 2, bars 29 to 32, incorporates the most contrapuntal texture of the movement. It is based on a new motif first heard in the right hand part of bar 29. The right hand's repetition of this motif is juxtaposed with a transposition of the motif down an octave plus a third in the bass, yielding a succession of parallel intervals of tenths between the two hands. Parallel intervals of this nature continue through to bar 31. In bars 29 to 31 there is a contrapuntal texture within the right hand part: a sustained note in one voice is juxtaposed with the new motif in the other voice. The motif's stepwise descent in bar 31 leads to a minor-third chord (B♮, D♮) in the right hand on the first beat of the next bar. The final note in this bar, G, in the bass, confirms that the harmony is now anchored in G major, the dominant of the dominant of the home key. Mozart is clearly setting his sights on returning to the tonic by announcing the start of Part 3.

Part 3, bars 33 to 36, opens with an exact transposition of the first subject from bar 1 by the interval of a fifth. What was previously heard in the tonic of F minor now sounds in the key of the dominant minor, C, confirming that Mozart is preparing a large-scale return to the tonic. In bar 36 the left hand gives the thematic motif starting on the note C, which is identical to the opening motif from the Exposition now sounding two octaves lower. This constitutes what is known as a "false reprise," a device that can be traced as far back as JS Bach.[3]

Recapitulation (bars 37–60)

Like many of Mozart's recapitulations, the Recapitulation of the second movement of KV 280 stands out no less for its contrast with than for its similarity to the Exposition.

Like the Exposition, the Recapitulation divides into three discrete parts. Part 1, bars 37 to 42, represents a compressed version of its homologue in the Exposition.

As was the case in the parallel section of the Exposition, Part 2 of the Recapitulation, bars 43 to 56, yields a three-part division as defined by key harmonic steps: (i) F minor (bar 43); (ii) C major (bar 48); (iii) F minor (bar 51).

Bar 51 announces the second subject transposed to the tonic. From bar 53, Mozart deviates from a precise transposition; bar 20 from the Exposition is then transformed and expanded into a three-bar group.

Part 3, bars 57 to 60, comprises a varied transposition of its homologue from the

3 A case in point is Bach's Sonata for Flute and Harpsichord in A Major, BWV 1032. The third movement is based on three-part binary form. The false reprise of the opening theme occurs towards the end of the middle section in bar 188. The real reprise, marking the start of the third section, occurs in bar 209.

Exposition, evoking yet again the grace and skill of a dancer's step.

Conclusions

In the second movement the number 3 manifests itself on multiple levels. Mozart's decision to cast the movement in sonata form results in a three-part division: Exposition, Development and Recapitulation. Moreover, the Exposition's most fundamental harmonic progression (F minor to A♭) is defined by the interval of a third. In terms of texture, the Exposition itself divides into three discrete parts. The same applies to the Development and the Recapitulation. The middle part of the Exposition is itself susceptible to a tripartite division. The same applies to the parallel section of the Recapitulation. In the Development, the form is not only three-part but ternary, comprising three parts: Parts 1 and 3 are based on the same thematic material.

All three principal sections (Exposition, Development and Recapitulation) incorporate networks of motifs in which the interval of a third comprises an integral part.

At the smallest level, the number 3 prevails. The harmony is defined by the triad. The meter is 6/8, comprising two groups of three notes or two triplets.

While it has become standard practice for analysts to consider individual movements of pieces from Mozart's era in isolation, the division of Mozart's Sonata KV 280 into three movements cannot pass unnoticed.

Given Mozart's strict Catholic upbringing, he was imbued with the symbolic importance of the Holy Trinity from a young age. In light of this background, it is conceivable that Mozart, in suffusing the second movement of his Sonata KV 280 with the number 3 at multiple levels, was influenced — consciously or subliminally — by the symbolism of the Holy Trinity.

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Society and information

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Introduction

In a presentation to the Royal Society of New South Wales on 7 July 2021, I proposed a high-level *view* of society — the information view — in which the individuals are identical information processors that form a society by interacting via the exchange of information (Aslaksen, 2021). A pictorial representation of this view is shown in Fig. 1, and as the view was incorporated and further elaborated in a later publication (Aslaksen, 2023), I will reference that where appropriate.

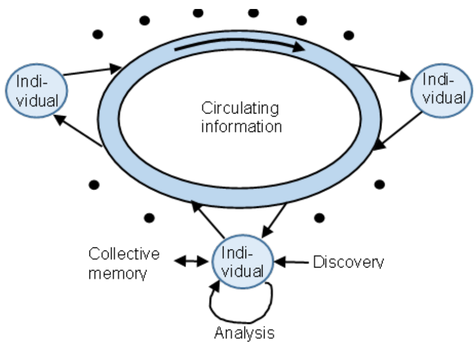

Figure 1: A pictorial representation of our high-level description of society. The circulating information is accessed by and added to by the individuals; discovery is a means for individuals to obtain information from their environment through targeted actions (e.g., measurements), with the interaction with the collective memory sources (archived information) shown separately. Analysis is the creation of new information through processing of information stored in the individual's memory. (Aslaksen 2023)

In the high-level view of society as an information-processing system illustrated in Fig. 1, the individuals are all identical as processors; that is, they have the same ability to process and store information, and their capacity to interact with the circulating information and with the environment is the same, but the content of the information, as opposed to the quantity, is different for each individual. But because they are identical processors, we may consider not the individual-to-individual interaction but introduce the concept of *the individual's interaction with society* in the form of the individual's interaction with a *circulating information*, i.e., the information produced by all the individuals.

However, in my work so far, the key concept of information was not defined; this was avoided by using it as a catch-all for data, knowledge, belief, sentiment, etc. The purpose of this paper is to consider how a more detailed description of information can be developed based on its relation to data and knowledge. The result is not so much a definition of information, in the sense of a statement of what it *is*, as is provided, e.g., in a dictionary, but rather a set of statements about what it must fulfil, whatever it is; requirements on "information" as it is used in the information view of society.

A concept of information

Statement 1: The purpose of information is to enable the transfer of knowledge between persons.

That immediately begs the question: What is knowledge? Knowledge is created by either of two processes. One involves the *observation* of our environment, both natural (including other humans) and created by humans. The observation may employ various instruments and devices, and the observed quantities — the data — may be converted into various physical forms (acoustic, optical, electrical) and be transmitted in any of these forms from the observed object to the observing individual, and via a number of segments, such as an analogue segment (4–20 mA link), a fibre-based digital segment, and a Wi-Fi segment. This is, in our definition, not transmission of information, but of data. Only when the observed data are accessed through our senses and then processed do the observed feature of the environment become part of our *personal knowledge*. For example, when we observe the structure of DNA, we can extract the knowledge that it is a double helix. The observed object does not contain any knowledge, as knowledge is a feature of the human; it requires a knower, but it contains the raw material from which knowledge can be created; in this sense the environment is the *source* of knowledge.

The other process is the processing of personal knowledge stored in memory, i.e., by thinking or what in Fig. 1 is called *analysis*. By recognising relationships between items of knowledge they form a system, and new knowledge may be created as emergent properties of this system. This "second order" personal knowledge is what is generally called *understanding*.

Statement 1 can be compared with a statement in the article (Dienes, 2012): "In my personal opinion, information in HMI studies — in an actual situation, and for somebody — should be understood as data on a carrier, which, if used, modify one's beliefs concerning something," where Dienes uses "belief" where we would use "knowledge."

The processing of data into knowledge depends on the cognitive background of the person; two persons accessing the same data will produce different personal knowledge, with the difference depending on the difference in cognitive background. The cognitive background is basically the knowledge stored in a person's memory.

Statement 2: Information is created in a process by which a person transforms a part of its personal knowledge into the form of a *message* that can be transmitted to another person or persons with the intent that the recipient will be able to extract knowledge from it.

There are several things to note about this statement. One is that, in addition to being created by humans, information is a *social* concept. (In a universe of one individual, there can be data and knowledge, but no information.) The second is that the only difference between information and message is one of quantity; a message is simply an identifiable quantity of information (see below). The third is that the originator may or may not intend the recipient to gain the same knowledge the originator has. In either case, the "packaging" of the knowledge for transmission as information depends on the originator's knowledge of the recipient's cognitive background. The fourth relates to our view, where transmitting information means including the information in the circulating information — with the intent of making the personal knowledge *public knowledge*. However, as the extraction of knowledge from the information will depend on the cognitive background of the recipient and thus, if the knowledge could be parametrised by a variable, say, q, the knowledge extracted by the members of society from a single item of information placed in the circulating information would be represented by a distribution, $p(q)$. The effect of the collective intelligence — the public discourse — should be to reduce the variance of this distribution, i.e., to produce a consensus. But in practice there are several factors that pervert this ideal operation of the collective intelligence, as detailed in (Aslaksen, 2023).

> **Statement 3**: The knowledge extracted from the information constitutes the information's *meaning* to the recipient.

That is, information has no meaning on its own, the meaning is only revealed once the information is received by a particular person. This is analogous to the information carried by a qubit; it is only revealed once it is measured at the receiver. We could say that the information carries within it all the meanings that can be assigned to it by all intended recipients.

It is interesting to compare the concepts of the three entities — data, information, and knowledge, as well as their relationships, presented here — with those found in the literature. A good source is the article (Zins, 2007), which presents the results of a study involving 44 academics and professionals within Information Sciences. One result was that "many scholars claim that data, information, and knowledge are part of a sequential order. Data are the raw material for information, and information the raw material for knowledge." But not all panel members agreed with this simple sequential order, and Raphael Capurro called it "a fairytale." In our high-level view of society, data is the raw material for personal knowledge, personal knowledge is the raw material for information, and information is the raw material for public knowledge. Information is placed in the circulating, or public, information, from which members of the public can extract knowledge. It follows that while information can be stored in various media, such as print and electronic media, the human mind does not store information. It receives and transmits information, but it stores knowledge.

Also, the article proposes a number of models on the basis of locating data, information, and knowledge in either the universal domain (our public domain) or in the subjective domain (our personal domain), shown in Fig.1 in the article. In our "model," information is the carrier of knowledge between the two domains; the format of this carrier depends on the technology used for transmission.

A structure of information

The high-level view of society as an information-processing system is an *unstructured* view, in that the individuals and their interactions are identical; this is similar to the use of *per capita* quantities in economics. However, within that view we can increase the level of detail in the description, and as a first, small step in that direction consider the following very simple model of a message transmitted between an originator and a recipient, consisting of three components:

1. The data that formed the raw material for the originator's knowledge;
2. the knowledge resulting from the originator's processing of the data; and
3. the additional context the originator believes the recipient will need to extract the knowledge.

The third component of this model makes the distinction between information and message explicit, and it shows that the information is "tailored" to the intended recipient, and we characterise the recipient by introducing the concept of a *role*. An individual can take on a range of roles, in the simplest case restricted to two roles: generalist and specialist. The generalist role is the one we all play every day; it comprises many detailed roles, such as those defined by family relations, by recreational, social, and political activities, hobbies, etc., and presumes a level of education that is average in the society in question. The specialist role is played when persons are engaged in the work for which they are trained, either in a trade or in a profession requiring a significant level of higher education and/or training. These roles comprise numerous more detailed roles associated with particular disciplines. We can note that this division is the same as the one made by Émile Durkheim — between "the political society as a whole and the special milieu for which he is specifically destined" — in Durkheim (1970: 71).

Consequently, the information processed by people falls into two groups: general and special. In reality, some people will spend most, or even all, of their time in the role of generalist, and some people will divide their time between the roles of specialist and generalist. In our view, with its identical individuals, the individual spends a proportion, say *h*, of its time or effort in the specialist role, and the circulating information can, consequently, be separated into two parts: a special part and a general part.

In the course of the evolution of society, with its steadily increasing specialisation and division of labour, the value of *h* has been increasing, and the creation of new information has shifted towards the special part of the circulating information. However, some of the knowledge embedded in that information has *implications* for the general part, and so transferring those implications as information to the general part of the circulating information is an increasingly important responsibility for the specialist. Or, in our view, the transfer of information between the two parts of the circulating information becomes an additional and increasing duty for the individual. This activity is indicated in Fig. 2, which also shows the separation of the circulating information into two parts.

Classification of information is not new, but due to our simple general/special division there is mostly only a weak correlation with these other classifications. In his essay *Probleme einer Soziologie des Wissens*, Max Scheler (Scheler, 1924) distinguished between *cultural data* (ideas, beliefs, values) and *real factors* (data about the structure of society). In Karl Mannheim's *Ideologie und Utopie* (Mannheim, 1936) a distinction is made between *exact sciences* and *cultural sciences*, and in Herbert Marcuse's *One-Dimensional Man* (Marcuse, 1964) the second dimension is essentially the processing of general information. The distinction is also expressed in various works on education, such as the *specialised* and *general* components in Émile Durkheim's *Education and*

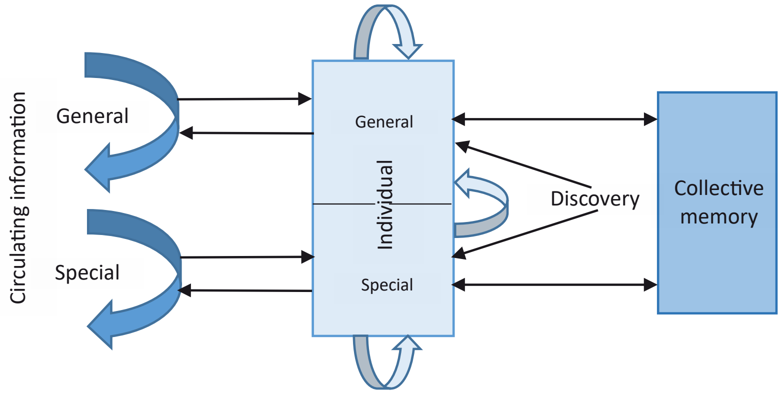

Figure 2: The modification of Fig. 1 to display the two roles of the individual, and the associated splitting of the circulating information into two parts. The three internal flows are flows of knowledge and the Discovery input is a flow of data; all the other flows are information flows.

Sociology (Durkheim, 1970) and in *What is an educational process*, by Richard S. Peters (Peters, 1967), his *principles* correspond approximately to our class 3 information.

With the splitting of the circulating information, the operation of the processing system — the collective intelligence — also displays two somewhat different behaviours. When it is operating on the general part, the behaviour is much as before: with regard to the general information it is a dialectic process aiming at reconciling differences arising between existing and new information and moving the consensus forward in response to changing circumstances — changes driven to a large extent by new applications of technology. It is this process that drives the evolution of society, as detailed in (Aslaksen, 2023). But when it is operating on the special part, it is mainly a matter of fitting the new information into the paradigm of the relevant discipline; such paradigms have, by their nature, a version in the Special domain and a version in the General domain, as e.g., the earth-centric paradigm had a place both in astronomy and in the popular understanding of the universe. Changes to such paradigms — scientific revolutions — are governed by a different process, as described in Kuhn (1962), but the result is a transfer of knowledge from the Special to the General domain, as indicated in Fig. 2.

We would hope and expect that this high level of information exchange, as it becomes increasingly international, would lead to effective cooperation on solving the serious global problems facing us: world war, Quality of Life inequality, global warming, and pandemics. However, here we come up against the difference between being able to do something and actually doing it. To explain this in the current context, we make two further simplifications. The first simplification is a modification of the previous division of the *content* of the information being exchanged into two classes: One, the information related to maintaining our existence, information that we might classify as *facts*. Two, the information related to our view of life, information we might classify as our *beliefs*. The second simplification is to divide the information according to *how it is transmitted*: One, by teaching, so largely *one-way*, as in education. Two, by interpersonal discussion, i.e., *two-way*, or what on a society-wide basis is identified as the public discourse. The result is a very high-level characterisation of the information exchange in the form of a 2×2 matrix:

	One-way	**Two-way**
Facts	Teaching	Research
Beliefs	Indoctrination	Discourse

If we then represent the strength of the interaction (i.e., the flow of information) by the parameter α and the capability of society to turn the information exchange into action by C, we now have a 2×2 matrix, α_{ij}, with each component showing a different development through history. And, correspondingly, we have four components of capability, C_{ij}, as follows:

- C_{11}: to increase the size of current society, i.e., more of the same.
- C_{12}: to increase our understanding of Nature and our ability to benefit from it.
- C_{21}: to maintain our current beliefs and the current form of society.
- C_{22}: to change our beliefs and transform society.

In terms of this picture, the problem we are facing is that in the great flow of information, and hence in the high value of α, the value of α_{22} is very small and, correspondingly, so is the capability C_{22}. The public discourse has been almost completely supressed by commercial and vested interests, so that instead of a dialectic process we have statements of beliefs and opinions — effectively a form of advertising. This situation was lamented some time ago by Herbert Marcuse in his essay *One-Dimensional Man* (Marcuse, 1964). For the public discourse to function, there needs to be tension in the first place; it only becomes active when the individual perceives a conflict between the social environment in which it is embedded and its own identity. Acceptance of this conflict as a prerequisite to progress is central to Marcuse's critique of modern society. Referencing Hegel, he states that the power of the negative is the principle which governs the development of concepts, and contradiction becomes the distinguishing quality of reason (Marcuse, 1964: 171). And concept is taken to designate the mental representation of something that is understood, comprehended, known as the result of a process of reflection (Marcuse, 1964: 105). It is this dialectical mode of thought that Marcuse calls *negative thinking*. Negative thinking is the driver of Marcuse's second dimension of the development of society; the driver of the first dimension — *positive thinking* — is the acceptance of the perceived world as the basis for reason. The difference between the two modes of thinking is reflected in the difference between "is" and "ought" (Marcuse, 1964: 132).

Some further thoughts

The application of our definition will raise several issues relating to the existing information and social science literature, some of which can already be anticipated. Foremost might be the lack of reference to the work of Claude Shannon (Shannon, 1948). The reason is simple: Shannon's theory is about the communication between a source, S, and a destination, D, both of which are represented by a set of states: $S = (s_1, s_2, ..., s_n)$ and $D = (d_1, d_2, ..., d_m)$. With each of these sets is associated a probability distribution, such that $p(s_i)$ is the probability of occurrence of

s_i, and correspondingly for $p(d_i)$. The quantity $-\log_2 p(s_i)$ is *defined* as the information generated by the source S by the occurrence of s_i. Correspondingly, the quantity $-\log_2 p(d_i)$ is *defined* as the information received by the destination D by the occurrence of d_i. The averages over the distributions are defined as the information produced by the source and received by the destination, respectively, and are called the *entropy* of the source and of the destination.

This is a completely abstract and axiomatic definition of information with no semantic content, as was emphasised by Shannon; its significance and application lie in being the foundation of a theory that is the cornerstone of modern communications engineering. It is clearly a very different use of "information" as compared with our use, as set out above, and there are many other interpretations of the concept, arising both before and after Shannon's article. A number of these interpretations are discussed in the article *What is Shannon information?* (Lombardi et al., 2014). One issue that arises is whether information is an abstract noun or a measurable entity, with it the assertion that, if an abstract noun, it does not serve to refer to a material thing or substance and cannot be a referring term. To this the authors bring the example of energy, which can be viewed as an abstract noun, but which at the same time refers to a large number of physical characteristics, each with its own unit of measure. There is

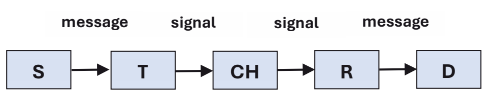

Figure 3: Shannon's model of communications. S = source, T = transmitter (encoder), CH = transmission channel, R = receiver (decoder), D = destination.

no reason why information cannot be similarly defined in several contexts, of which Shannon's theory of communications is one, and our view of society as an information-processing system another.

The issue here is that Shannon's theory of communication is concerned only with the transmission external to the persons involved in the communication; it treats humans as machines, which is why the theory works equally well for communication between humans (transmitting knowledge) as for communication between machines (transmitting data). Shannon's concept of information recognises neither data nor knowledge and makes no distinction between the two: what is being transmitted (the messages) is simply sequences of abstract symbols. In the article (Korogodin & Fajszi, 1986), the authors make a distinction between "information tare" and "information," with the former representing Shannon's information and the latter being something like the meaning of the information. But this still does not reflect the essential role of the individual. For the interaction between persons, Shannon's standard diagram of communication, in Fig. 3, needs to be expanded by including the human part of the process taking place within the Source and the Destination, as shown in Fig. 4.

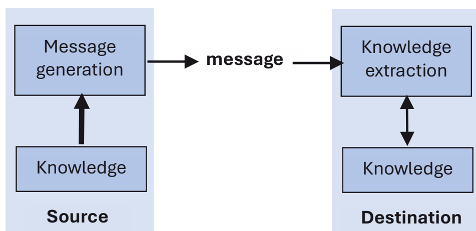

Figure 4: Elaboration of Source and Destination to represent persons and to show the transfer of knowledge.

In Fig. 4, the heavy arrow between Knowledge and Message generation in the Source signifies that this transfer of knowledge is a process reflecting an intention on the part of the Source regarding the knowledge to be received at the Destination — a process driven by the person's *will*. The double-headed arrow at the destination signifies that the extraction of knowledge from the message is a process of *evaluation*, described in some detail in Aslaksen (2023), so that the extracted knowledge depends on the person's existing knowledge.

The issue of the difference between how the concept of information is treated in information technology and in sociology becomes particularly visible when we address the question of how to measure information, and it is an issue that reflects the basic difference between the physical and social sciences. If the subject matter of this essay had been physics, one of the central concepts would be that of energy and on introducing it, e.g., in the form of mechanical work — force multiplied by distance — we would give its measure in terms of basic units — $kg \times m^2 \times s^2$, or joule. Information technology is situated within the physical sciences, and the unit of information is the *bit*. The information transmitted over a channel in a given amount of time is simply the number of bits transmitted. But that this measure has little to do with our concept of information is demonstrated by considering an item of information being transmitted repeatedly; the number of bits transmitted increases in proportion to time, whereas the information transmitted remains fixed.

In closing, it is important to realise that our item of information remains an intuitive concept and cannot be measured in terms of any physical quantity. But the statement "what cannot be measured does not exist" is too simplistic when dealing with human concepts and thought processes, and the little diversion into Shannon's theory of data transmission was intended to demonstrate the complexity added when source and destination are replaced by humans. Examples of an analogous increase in complexity are: going from integers to real numbers; from bits to qubits; and from robots to humans. This does not mean that the simplified concept is not useful — on the contrary, simplification may increase the usefulness, but it should not be a limitation on our quest for understanding.

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History of western science: A tour sponsored by the Royal Society of NSW, and the State Library of NSW (Sept–Oct, 2019)

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Introduction

When invited to construct and conduct a tour to experience the history of western science, acceptance of the challenge was a naïve belief that the objective could be achieved by stringing together a series of site visits between Venice and Cambridge. The "official" tour began in Padua, the university town serving Venice, but a short pre-tour visit to Venice was joined by several of our group.

The itinerary for the tour included visits to gardens, museums, universities, colleges and laboratories, but it was the "up close and personal" experiences that would leave an unforgettable memory for us all, including a sense of how science of today came about through the lives of those whose ideas shaped the world we know.

Highlights

It would be churlish to separate out "highlights" with so many, although it may be helpful to identify "Big Moments" that shaped our travel experience and also shaped western science. These are summarised in the attached figure as 28 "moments" linked to their disciplines and to the evolution of ideas into the 20th century.

Italy

The University of Padua was where it all began; where through the ideas of Copernicus, Vesalius, and Galileo, empiricism and experiment replaced mysticism. Here a heliocentric solar system, structure/function relationships in biology, and the development of mathematics as the language of science, all began. Visits to the Physic Garden, its library and herbarium showed where classification and study of medicinal plants paved a way for botanical science, and by extension with later scientific study of plants in terms of their environment. The latter was demonstrated through a visit to the adjoining Garden of Biodiversity, providing an unique opportunity to grasp 500 years of ideas that were the backdrop to evolution and genetics that we would see later in the tour. Visiting the first anatomy theatre underpinned the importance of anatomical dissection, and seeing Galileo's podium was a reminder of his significance to science. Florence was Galileo's town, and the exhibitions in the Museo Galileo were a stunning reminder of his enormous contributions to knowledge.

The Renaissance history of Florence illustrated for us the importance of a partnership with government (here the Medici family) and its immediate relevance to everyday life. Such a partnership arrangement as the Academia del Cimento (1657) was established in Florence by students of Galileo and the Medici. Although lasting only a decade, this would provide a basis for Enlightenment ideas.

A short visit to Bologna was a reminder that here began the first of the great universities in Northern Italy and that Luca Ghini, who began Physic Gardens and Herbaria and his influencial student Ulise Aldrovardi who began the discipline of Natural History, both studied in Bologna. Aldrovardi's extraordinary eclectic collection is housed in the Palazzo Pogi, which also houses contributions from other giants of western science, including Galvani. His experiments on the generation of electricity and its role in nerve conduction was a major convergence point for biology and the physical sciences. Galvani's studies established the pathway to discovery of storage of electricity in batteries (the voltaic pile) by Volta in Pavia in 1800, and was an essential step to the work by Faraday (whom we meet at the Royal Institution in London).on electromagnetism.

France

Visits in Paris demonstrated continuity with Renaissance Italy and moved earlier ideas forward to the Enlightenment. As the practical outcomes in western science were developing, these outcomes were in part driven by the French Revolution. Visits in Paris illustrated many of these developments, including an organisational basis to science with Royal support for the establishment of the Academie de Sciences (1666). An explosive growth of study in natural history was driven by the Great French Expeditions of the 18th and 19th centuries. This is evidenced by their maps held in the Biblioteque Nationale and the early ideas on Evolution and Comparative Anatomy, seen in Jardin des Plantes. We visited the "home-museums" (or variations of same) of great French Scientists (Lavoisier, Pasteur, and the Curies) and the Musee des Artes et Metiers, demonstrating the sophistication of the "French Industrial Revolution" and how progress in science is dependent on precise measurement. A recurring theme throughout our journey. Two memorable visits were to the Academie de Sciences and its archives and to the Biblioteque Nationale. The Academie holds a "packet" for every French scientist of note, containing manuscripts, letters and personal memorabilia. The Academie was where the first presentations on radioactivity were given by Becquerel and Curie. At the Biblioteque Nationale we saw the only complete Mercator 1569 world map and manuscript, as well as rare printed maps from Pacific exploration by the French in the 18th and 19th centuries.

London/Cambridge

Science in London was more focussed — on one hand the Royal Society and later, the Royal Institution, dominated organised science in England, while on the other the Industrial Revolution and applied science through use of steam (as seen at The Science Museum) and electricity (the Royal Institution), powered Imperial England.

Two museum visits illustrated the development of navigational science and natural history as dominant strands in Australian science, introduced respectively by James Cook and Joseph Banks. At the Greenwich Observatory, commissioned by Charles II in 1675, specifically to identify a method to determine longitude for predictable and safe navigation, we gained insight into navigational scientific developments. The Linnean Society holds the collections (acquired through the influence of Banks) that established England's pre-eminence in natural history and became a focus for both Darwin's and Wallace's theories on natural selection. The Linnean Society visit was complemented by an afternoon in the house and garden of Darwin's Down House.

The day in Cambridge was extraordinary, starting with a morning visit and talk at The Cavendish Laboratory. It is here that twenty Nobel Prizes have been awarded, over eighty years, for work influenced by great leaders of atomic and molecular physics, including Maxwell, Thompson, Rutherford, and Bragg, with studies related to electromagnetic spectrum, sub-atomic physics, and molecular structure, determined in part by X-ray diffraction. A talk by retired Head of Department, Malcolm Longair, was followed by a tour of the museum containing much of the "Heath-Robinson" constructed equipment used to produce early models of the atom and the structure of protein and DNA. The day in Cambridge visit was completed by a visit to the Sedgwick Museum of Earth Sciences with its comprehensive overview of the history of British geology, including a copy of Smith's massive Map of the Geology of England using fossil records to join the strata dots, and also early records of recognition of "older" strata — Cambrian/Devonian/Silurian — by Sedgwick and Murchison, based on a fossil record in Wales.

The context

The broad context of the development of western science was examined through its relationship with, and impact on, society. At the same time we traced through visits, a parallel evolution of art from late middle ages (Giotto's Fresco Cycle in the Scrovegni Chapel, Padua, with its break from rigidity to realism, emotion and perspective), through Renaissance art (at the Uffizi, Florence — from Botticelli to Caravaggio), and then to 20th century art movements (in the Pompidou Centre in Paris). Sienna was visited to see secular government and the impact of the Black Death (which signalled the end of Feudalism), as a critical point in the development of a democratic western society.

As medicine and health management have always been a barometer of society, we visited several centres of medicine, including the Scuola Grande di San Marco built in 1500 in Venice, where secular medicine developed and which now includes a magnificent display of medical texts; the Padua Hospital of San Francisco that operated for 400 years as a teaching hospital for the medical school of Padua (now home to a very modern History of Medicine Museum, tracing the impact of science on practice); the completely secular hospital in Siena, with wonderful frescoes, which straddled the via Francigena, an important trade route to Rome. This hospital serviced pilgrims from 900 AD. Continuity of medical science was through a visit to the Santa Maria Nuova Hospital in Florence, in continuous use since 1288, with its innovative Pathology Museum, early pharmacology and important library housing many foundation documents of science donated by wealthy patrons. These included a first-edition text of Galileo.

The people

Science at the end of the day is about people and that was the core of our trip. Two groups must be recognised, without whom this would have been a sterile and uninteresting experience. First, my friends and colleagues who came with us on this unique thematic tour of western science. We introduced an "open communication platform," with many contributing brief talks about and around science — usually as we travelled by coach. The talks ranged from Omega 3, to aircraft technology, geology, education, control of atmosphere in a Biodiversity Garden, Black Holes, botanical illustrations etc. Thank you, team RS(NSW)! Second is a remarkable group of contacts who gave time and tolerance to us. These "guides" were a special group of experts who contributed beyond any reasonable expectation.

Italy

Professor Giorgio Zanchin, Professor Neurology, Padua, for organising much of our tour in Padua, especially "his" new History of Medicine Museum. Professor Barbara Baldan, who gave an afternoon of her time to ensure we had an extraordinary tour of the Physic Garden, the Library and Herbarium and the Biodiversity Garden. In Florence, Professor Donatella Lippi and her network of contacts, both in medical history, Renaissance art as it applied to science, and in Florentine society through the Lyceum Club (which hosted an evening of food and music that we will not forget).

France

Professor Pierre Corvol and his impressive colleagues at the Academie de Sciences in Paris, where "thank you" can never be enough. Similarly, Catherine Hofmann and her colleagues put in much effort to bring out of hiding a stupendous collection of manuscript and printed maps recording the (export of) French Enlightenment. The reception hosted by Brendan Berne and co-ordinated by Harriet O'Malley at the Australian Embassy was a major contribution to the credibility of Australian Science and thank you for inviting our colleagues from the Academie de Sciences and the Biblioteque Nationale.

England

Thanks in particular to Rupert Baker (Librarian, Royal Society), Professor Frank James (Royal Institution) and Isabelle Carmentier (Linnean Society). Malcolm Longair (retired Head of Department) ensured a memorable morning at arguably the most important Institute relevant to Australian science: the Cavendish Institute.

Two guides deserve special thanks — Emily Akkermans, Curator of Time at the Royal Museums Greenwich, and David Rooney at the Science Museum — how good was he!

And, the Australian connection

An objective of our trip was to relate the History of Science in Europe to scientific achievement in Australia. Elsewhere (Clancy, 2020) I have given my view that the attainment of Australia as a nation, with the highest standard of living, occurring within a century of being a gaol of 1000 people, at the far end of the world, was largely due to an Enlightenment-driven process where "everyone was a scientist" identifying and solving problems by "empiricism and experiment."

A second layer of scientific achievemnent came with university development in the 1880s and that involved a shuttle system involving English and Australian academics. We had the opportunity to examine aspects of this idea,looking at the "sciences" of Cook and Banks (Navigation science, and Natural History) and through the key role played by The Cavendish and Cambridge. These institutions provided academics to young universities in Australia and also trained bright students who would later return to take leading positions in Australian universities (e.g. Oliphant, Burnet, Eccles). Some stayed to contribute to English academia (e.g. Harris, Florey, Cameron, and Cornforth), and especially Lawrence Bragg, who would follow Rutherford as Director of the Cavendish. Later at the Royal Institution, he introduced X-ray crystallography to be used to determine structure of proteins and DNA. Young English graduates with little chance of promotion in the UK would develop their reputation in Australia before returning to lead science across many fields in Britain, and pick up the odd Nobel Prize.

Darwin maintained contact with colleagues in Australia, and had great influence — in part related to Farrer (a distant cousin) and his use of wheat selection through variation of environment. Also Darwin's influence is seen with the switch towards ecology in the latter part of the 19th century, and the development of Evolutionary Anthropology. Analysis of natural plants encouraged Robert Robinson, a young academic chemist who developed his reputation as the Foundation Professor of Chemistry at University of Sydney.[1] He returned to England and was later awarded a Nobel Prize for synthesising alkaloids via amino acids. Completing the shuttle system underpinning the development of academic science in Australia, Robinson became mentor to Sydney graduate John Cornforth, whose Nobel Prize also related to organic synthesis.[2] The Royal Society played its part here.

In France Pasteur sent his nephew Adrian Loir to Australia to win a prize for eradicating rabbits using the chicken cholera bacteria (which surprisingly was not supported by the Australian poultry industry). Along the way Loir, through vaccination, solved the problem of anthrax infection which was killing 400,000 sheep a year. He established a Pasteur Institute in Sydney Harbour.[3] An understanding of these extraordinary interactions and formative relationships underpinning Australian science and the international connections that continue was an important outcome of our many visits to the great institutions in Europe where both our early academics and those that followed, gained experience.

Conclusion

This overview of our trip will be associated with "28 Moments," identifying key flexure points in western science (we touched base with 70% of these) and "Day Notes." Perhaps the main "missing" scientific contributions came from Germany in the second half of the 19th century (Bunsen and spectroscopy opening the chemistry of space; Planck and Einstein and subatomic physics,

1 See Robinson R and Smith HG (1914) A note on the phenols occurring in some Eucalyptus oils. *J. & Proc. of the Royal Society of N.S.W.* 48: 518–519. [Ed.]

2 See Cornforth JW (2018) Adventures with sugars. *J & Proc. of the Royal Society of N.S.W.* 151: 125–134. He had earlier, in 1937–38, published five papers with us. [Ed.]

3 See Loir A (1891a) Notes on the large death rate among Australian sheep, in country infected with Cumberland disease, or splenic fever. *J. & Proc. of the Royal Society of N.S.W.* 25: 46–52; and Loir A (1891b) Notes on a spontaneous disease among Australian rabbits. *J. & Proc. of the Royal Society of N.S.W.* 25: 89–93. [Ed.]

Schwann — the cell, and Wohler — organic chemistry, Virchow — cellular pathology, and Kock in microbiology. This names but a few.

However, we were successful in tracing "big pictures":

- In Biology, we went from classification, structure and function, to evolution and genetics, and ecological relationships between the organism and the environment.
- In Physics, we went from mechanical forces and related laws though the electromagnetic spectrum and subatomic studies including radioactivity and new laws all based on mathematics.
- In Astronomy, we began with a heliocentric solar system, but moved to understanding a dynamic expanding universe, powered by nuclear fusion. Along the way longitude was sorted with accurate time pieces, and "navigational science" became of great practical importance.
- Chemistry was a late starter due to the need for sensitive instruments to measure products of reactions and a reliable and steady source of heat to drive the reactions. Lavoisier used such measurements to show combustion and respiration were the same process, while Davy began serious work defining the Periodic Table. This took shape in 1869 when Mendeleev organised elements in groups according to atomic mass.
- Earth sciences began as geography, defining the land masses, as recorded by Mauro and then Mercator and seen in their respective maps in the Biblioteca Marciana in Venice, and the Biblioteque Nationale in Paris. Then came English and French cartographers. Geology developed more in parallel with practical mapping in Australia. With Plutonic Theory winning over the Neptunists, followed by Hutton, Lyell and Smith representing Geology with immense time periods. Geological time observed by Darwin looking at the valley system from Wentworth Falls inspired his idea of evolution occurring over great time periods and enabling selection. Fossil records chimed in with interests in comparative anatomy, contributing to natural selection and evolution (Cuvier and visit to the Jardin des Plantes in Paris). Extinction periods continue to baffle (first identified by Cuvier) while the underpinning principle of plate tectonics was first suggested by Abraham Ortelius observing "continental matching" on his 16th century world map (in the Biblioteque Nationale).

The success of the tour unquestionably followed the connection with the Royal Society of NSW. This recognition plus the connection with the history of science in Australia created for us all a deep appreciation of our European roots, and the continued respect held for the contributions to science made by Australians. The connections were ever present — even the herbarium from Labillardiere's visit to Esperance Bay in Western Australia in 1792, appears in Florence!

I doubt the success of our visits could easily be reproduced. Our tour was unprecedented, as theme-based and tracing a comprehensive history of western science from essentially "Galileo to Rutherford" or "Luca Ghini to Pasteur" or "Cuvier to Darwin".

In putting the tour together the year before our tour, Christine and I literally knocked on doors. One door was the Academie in Paris. The President was in his office.

It helped that we were both immunologists and friends of Gus Nossal. He insisted that the Academie provide a lunch — delicious — and in return we arrange a reception at the Australian Embassy to which Fellows of the Academie would be invited. That required organisational challenge, but, with the help of Peter Baume, it was achieved. Similar positive outcomes occurred with every institute we approached in Italy and England.

The key to the remarkable cooperation essential to success, was a combination of the novelty, the Royal Society connection, and the "knocking on doors"!

28 Moments in a history of western science

Emeritus Professor Robert Clancy AM FRSN

Introduction

At the outset, let me be frank![1] To even attempt to reduce the extraordinary story of western science into "28 moments" is grossly simplistic, gives scant credit to those many great men and women who made important discoveries who ate not included, is artificial and constrains the evolution of ideas in controversial ways. This said, it is my attempt to give a context to the great turning points that characterise the development of science as we know it today. We all have learnt, to our chagrin, that unique and original ideas are rare indeed. Rather, knowledge grows in incremental ways — as Gribbin in his *History of Western Science 1543–2001* claims — it is all about being in the right place at the right time. He states that, had not Newton enunciated his Laws of Motion and Gravity in his *Principia* in 1687, someone else would have done so, perhaps 10 to 20 years later. That to me is a little unfair on those that stand as greats at an inflection point in the evolution of scientific knowledge. But there you are! Here, with all its faults, are my "inflection points" in the acquisition of scientific knowledge, which I call "the 28 moments in science" (or "Big Science"), arranged for the purpose of giving a sense of order and context to the sites we visit in our Padua to London History of Science tour.

- First, more than 75% of these "moments" occurred in the three areas we visit: the city States of Northern Italy, Paris and London (and surrounds).
- Second, I have arranged these "moments" into four divisions, what we recognise today as (i) Biology (study of life); (ii) Classical Physics and Astronomy (strands study of matter and energy and their relationships); (iii) Chemistry (identity and character of matter); and (iv) Earth Sciences.
- Third (and with a little licence), the stages of development of these six "divisions" are divided into "early," "mid," and "recent" periods to give a sense of time frame to discovery.

1 Notes provided to those taking the History of Science Tour.

- Fourth, most discoveries are by well-educated polymaths, able to devote time to science due to financial stability. or protected time in the Church.

Research and discovery as we know it today is performed in funded institutions, enabling a democracy unheard of in earlier times. Prior to 1900, there were very few funded organisations: Académie des Sciences (Paris, 1666), The Royal Institution (1799) and the Cavendish Laboratory (1874). The two English institutes had a close relationship to Australia, especially the Cavendish, which became the central postgraduate training centre for those such as Mark Oliphant, who would later play pivotal roles in developing physics and astronomy in Australia, and in providing the blueprint for stable centres of scientific research (the other British institute crucial to Australian science — here biology — was the Lister Institute directed by CJ Martin (1903–1930) with future Nobel Prize winner Sir Macfarlane Burnet amongst many Australians to develop their scientific careers in the Lister).

Biological moments

Andreas Vesalius (1514–1564) who described human structure following dissection, with Nicolaus Copernicus (the heliocentric solar system) and Fra Mauro (the observed earth) were the pillar stones of western science. His description of human anatomy from dissection followed 1500 years of confused mythology based on Galen's dissections of a Barbary Ape. Vesalius moved around Europe, but Padua was his intellectual home. Modern medicine can be dated from 1543 and his publication *De humoni corporis fabrica fibri septuem*.

The immediate impact of his publication established a dynasty of scientific anatomists: Fallopius (1523–1562) and Fabricius (1533–1619) followed Vesalius, with the latter discovering venous valves, which was to influence his student William Harvey studying in Padua. Harvey would write *De Motu Cordis et Sanguinis* (1628) in which he recorded the discovery of the circulation of blood, establishing modern physiology as a discipline. Thus, the Padua school in essence established "structure-function" correlations as central to progress in biology. Marcello Malpighi (1628–1694) (Bologna) completed Harvey's "circuit" by using the recently discovered microscope to identify a "capillary" network connecting the right and left side of the circulation via the lungs (where gas exchange occurs in the alveolar sacks).

A sequence of extraordinary anatomists continued to add new observations, culminating with Giovanni Morgagni (1682–1771) an anatomist and physician in Padua of great repute (and with the highest wages ever given in the Venetian Republic). Amongst his many contributions was *De Sedibus et Causis Morborum* (1761), based on more than 600 autopsies, now considered the foundation of pathology and clinical-pathological correlations: the framework for all students of modern medicine.

Luca Ghini, a contemporary of Vesalius, but educated and working as a physician and botanist at the University of Bologna, would change the course of botany by establishing the first Physic Garden (at Pisa) and create the first herbarium (or collection of pressed plants) enabling the systematic study of plants. His student Andrea Cesalpino followed him as Director of the Pisa Physic Garden, improving classification of plants from an alphabetical system based on medicinal value, to a more generic system using fruits and seeds. His herbarium — one of the two oldest remaining — is kept in the Museo di Storia Natural di Firenze. Classification of flora and fauna began in these Physic Gardens but their connection with materia medica was limiting.

The main breakthrough of the 17th century was by the English botanist, John Ray, who established species as the ultimate unit of taxonomy. His major contribution to classification came in his *Historica Plantarium* in three volumes, published between 1686 and 1704, basing his classification for the first time on structural characteristics. it was his pioneering work that made possible the more practical classification by Carolus Linnaeus in the following century. But it was the classification developed by Antoine Jussieu (1748–1836) and published in 1789 that replaced the artificial system of Linnaeus (based on numbering stamens and pistols) with a natural system using multiple characters. This would prove of particular value to Darwin in identifying evolutionary characteristics: Jussieu was another "Jardin des Plantes" naturalist (see below).

The two "moments" in the second time frame (1700–1900) relate to the connecting concept of evolution, and a composite of related discoveries: the unit of life (the cell), inherited (genetic) influence, analysis of cellular events at a chemical level and the corollary of specificity (with respect to disease). Evolution is the "great idea" of biology and can be summarised as "the heritable characteristics of a population over generations." The recognition that all species are related and gradually change over time, and that man is no different to other species and subject to the same scientific laws, more than any other idea, rocked society and, even today, remains controversial. This variation is determined by genes, as identified by Mendel.

Genetic variation occurs by mutation or re-combination, with Darwin's great observation that evolution is based on natural selection within a particular environment, to favour survival and reproduction (though today the impact of genetic drift — a random process — is also considered important) i.e. natural selection and genetic drift are two processes that create in genetic variation. The "Modern Synthesis" or "Neo-Darwinian theory" now considered as biology's central paradigm integrating Darwinian evolution with Mendelian genetics, could be argued to have been composed by William Farrar working with wheat varietals in the late 1890s — a major yet unrecognised Australian contribution to science. Farrar's observation predated wider recognition of Mendel's observations.

Through the 18th and 19th centuries, there appeared a remarkable group of French naturalists with their work centred around the Jardin des Plantes, Paris. First amongst these was Georges-Louis Leclerc, Comte de Buffon (1707–1788), best known for his *Historic Naturelle*, published between 1749 and 1804 as the first comprehensive work on natural history.[2] His estimate of the age of the earth at 75,000 years may appear inconsequential today, but at ten times the age identified in the Bible, this was a huge step, gelling with his views of gradual evolution a

2 Buffon was also a mathematician: read about the Buffon Needle problem to estimate the value of π in Marks RE (2014) Monte Carlo. In: Augier M and Teece DJ (eds) *The Palgrave Encyclopedia of Strategic Management*. London: Palgrave. https://doi.org/10.1057/978-1-137-00772-8_709 [Ed.]

process that included man. Georges Cuvier followed Buffon at the Museum of Natural History becoming the expert in comparative anatomy and one of the most influential biologists in the world. His contributions in comparative anatomy in life became a blueprint for interpreting and classifying fossil remains. He shifted from recognising a linear system, to recognition of four groups, a watershed moment in zoology. Applying his work to fossil remains enabled the placement of strata "in age order," using the Paris basin as his laboratory.

Of the three great French "Jardin des Plantes" biologists of this time Cuvier, with his observations on comparative anatomy, was least inclined to support a dynamic evolutionary process. Jean-Baptiste Lemarck's focus was on mechanisms of evolution: his "transmutation" theory (1809) was based on the spontaneous generation of simple life forms that "inherited" changes caused by use or disuse. Indeed this was the best thought out idea before Darwin. lt was this group of naturalists that contributed to French Enlightenment with its influence on Laperouse and those that followed, especially through their Pacific voyages and the unavoidable contacts with 19th-century Australia.

Charles Darwin published his ideas at the same time as Alfred Wallace (in his "Letter from Ternate")[3] in 1858. There were differences in relation to whether man was included, whether sexual selection participated, whether selection operated on individuals or species, and the idea of pangenesis (or transmission by heredity of acquired characteristics).

The second and more complex "moment" was in the 19th century, and did much to explain the process of evolution, the "cell | gene | species" series of discoveries.

The central component of this discovery was the cell: an idea from the early microscopic studies of Robert Hooke (1665) and Anton von Leeuwenhoek (1676), but a more substantive "cell theory" was developed in plants by Matthias Schleiden and animals by Theodor Schwann, both in 1839. From these observations, two principles were deduced: (i) all living organisms are composed of cells; and (ii) the cell is the basic unit of life. In 1855 Rudolf Virchow added a third, (iii) all cells are derived from pre-existing cells. Fredrich Wohler (1800–1882) established organic chemistry — the chemistry of cellular activity — in 1828, by synthesising urea from inorganic substrates. This milestone achievement not only initiated chemical study of metabolism and cellular function, but put paid to the long-held view of vitalism (whereby a nebulous "life force" was essential for the synthesis of organic substances). By the second half of the 19th century the idea of a cellular basis for all living organisms with active chemical processes sustaining both the life and replication of cells was established, but determinants of heredity remained obscure.

In 1865, Gregor Mendel published work on 10,000 pea plants to identify the fundamental laws of inheritance. He deduced that "inheritance determinants" or genes come in pairs, with one from each parent. He traced the segregation of genes, finding that their product could be dominant or recessive and derived a mathematical pattern of the inheritance of traits. His work

3 See Beccaloni G (2022) The 'Letter from Ternate': what happened to Wallace's legendary 1858 letter and Darwin's reply to it? *The Linnean* 38(3): 16–24. [Ed.]

was not recognised until 1900. Hence the importance of Farrar noted above.

The outcome of the two great biological ideas of the 19th century — evolution by natural selection and the particulate- (gene-) dependent basis of variation that could be passed on to subsequent generations — was a race to understand the chemical basis of both genetic variation and heritable variability. This came with the construction of a model of double-stranded DNA with specific base pairing to enable exact copies. Mutations in germ-line DNA provide a source of new stable variants on which selection can act.

The idea of specificity in disease (remember, Galen's idea of balance of four humours had dominated thinking for 2000 years) came about following recognition that single cells surviving in the environment could parasitise multicellular organisms, sometimes causing damage. Louis Pasteur (1822–1895) identified such cells as bacteria and noted unique characteristics allowing classification and correlations with particular disease (i.e. infection was specific, not a disturbed balance of humours). He extended these observations to identify resistance mechanisms (initially as specific antibodies) in the host: the idea of the "Host-Parasite" relationship was born.

Classical physics moments

Physics is the natural science that studies matter and its motion and behaviour through space and time, and the related entities of energy and force. Here we look at the development of "classical physics," recognising the connection with astronomy with its focus on the broader cosmos and the universal laws that began with Galileo, continuing with Newton, Maxwell and Einstein. "Classical Physics" is the physics of our school experience — of forces, movement, light and magnetism — and was the bread and butter used by Newton in constructing his "Laws." In the context of our interest, the first "classical physicists" who used the scientific method were William Gilbert and Galileo Galilei (whom we discuss under "cosmos"). Both with medical training (as with most of these "foundation" scientists: Vesalius, Ghini, Harvey, Copernicus, Gassendi and Malpighi). Gilbert's experimental work on magnetism culminated 20 years' study, in one of the most important books on science, *De Magnete*. This was the first significant book on science published in England. He discovered how to generate magnetism and observed its polarity and recognised the idea of "the great earth magnet." Indeed, no further advance in the study of magnetism occurred for 200 years until the discovery of electromagnetism in the 1820s and the subsequent work by Michael Faraday.

There would be many, such as Hooke and Boyle, who would make significant contributions to "classical physics" before Newton. Importantly in northern Italy, and continuing the work of Galileo, was Borelli who studied man as a mechanical machine. Perhaps most important and influential in this early period, was the Frenchman René Descartes (1596–1650), a typically wealthy polymath who dabbled in a wide range of science and philosophy, publishing his ideas in a series of books beginning with *The Method* in 1637. His strength was a commitment to scientific method with contributions to the understanding of phenomena ranging from meteorology to the idea of inertia. One of his most influential discoveries was the use of numbers to describe position, leading to graphical representation, and the use of algebra to analyse geometry. These numbers are now known as Cartesian Coordinates, and contributed to the development of maths as the "language of science."

Such was Descartes' influence that his "incorrect" ideas (especially his rejection of the idea of "void") held back later ideas by Newton, because they conflicted with Descartes' "eddies" within a thin connecting "fluid" in space, and also the "atomic theory," which had minute particles bouncing around in a vacuum. Just as Descartes had enormous influence in France, so did his contemporary Francis Bacon (1564–1626) in England, whose influence on his countrymen was equally profound by emphasising a scientific method based on data collection and experiment.

Two important scientists whose studies were game-changing were Christian Huygens (1629–1695) and Michael Faraday (1791–1867). Huygens was Dutch but spent much of his working life in Paris and also "connecting" to the Royal Society. Again, a polymath — a mathematician, physicist and astronomer — his greatest contribution was in formulating the wave theory of light; at a time when many, including Newton, thought in terms of particles, he developed quality optics and made important discoveries in astronomy (including defining the rings of Saturn) and centrifugal force, as well as developing the pendulum clock to give accurate time for the first time.

Faraday brought the disciplines of magnetism and electricity together, creating the foundations for electric motors and generators, and bringing together technology and science in the period of the Industrial Revolution. To understand Faraday's contributions, one needs to follow the discoveries of electricity in the preceding century: from the development and storage of electricity in Leyden jars, through the studies of Benjamin Franklin (1706–1790) on storage and polarity of electrical charge, and the capacity of electricity to magnetise and demagnetise iron needles.

Together with others, including Mitchell, Priestly, and Cavendish, but best proven by Charles Coulomb using a torsion balance, it was shown that both electrical and magnetic forces obeyed an inverse square law. However, the greatest contribution came from the University of Bologna by Luigi Galvani in 1791, when he noted the generation of electricity when two metals (brass and iron) came in contact. This observation was built on by Allesandro Volta (1745–1827) in Pavia, who constructed the Voltaic Pile — a collection of silver and zinc discs, separated by cardboard soaked in brine — a battery capable of providing a steady flow of electric current (whereas the Leyden jar discharged its electricity in a single event). Thus, by 1800, scientists had a steady flow of current to study.

Then came Michael Faraday of the Royal Institution. Initially a technician for Humphry Davy, he would revolutionise technology by exploiting discoveries made in electromagnetism. He showed that an electric current in a wire forced the wire to circle a fixed magnet — the basis of the electric motor — within 66 years electric trains were running across the world! This was electromagnetic induction. Later he showed that moving magnetics could induce an electric current in a coil: the electric generator or dynamo had been discovered. He developed the idea of "lines of force," using iron filings, which from studies of magnetism, he concluded to be cosmos-wide, thus anticipating wave formation and the electromagnetic spectrum. He also solved problems related to electrolysis.

By late 19th century, the laws of classical Newtonian physics did not apply to observations made at the level of atoms, such as studies on electromagnetic waves and radiation emanating from atoms, for example, the photoelectric effect (i.e. an increase in the intensity of light on a surface did not lead to an expected emitted linear spectrum of energy). Planck postulated that the energy-of light is proportional to its frequency and a constant that relates them now known as Planck's constant (*h*); this led to Einstein in 1905 showing light exists in quanta of energy called photons. The duality (wave form and particle form) of electromagnetic radiation (EMR) became the basis of quantum mechanics and subatomic physics. Classical physics now gave way to the new physics of Planck and Einstein.

Astronomy and the laws of the cosmos

Nicolaus Copernicus (1473–1543) was a true polymath, a renaissance man in touch with mysticism, whose early training in law and medicine (and exposure to the "new thinking of the Renaissance") was in Padua and Bologna. His interest in astronomy and mathematics was philosophical as much as it was from the observation of planetary movements. The longstanding model of the "universe" (then the Sun, Earth, Moon and five planets) was that of Ptolemy, who had a central earth surrounded by the Sun, Moon and planets, in perfect circles. Copernicus did not accept the complicated models that differed for each planet that required epicycles, to "fit" the Ptolemy model, and he challenged the discrepancy of Moon size, where observation did not fit the Ptolemaic model, Copernicus developed a "neater" model where there were uniform equants for different planets. His model had a single (solar) centre for the planetary system, with no variation in rate of movement.

There were many unanswered questions, such as: the fixed position of stars (which he assumed were a longer distance away), there was no "wind" caused by the Earth's movement, and no "falling into the Sun." All problems for the next generation! His ideas of a heliocentric planetary system were published in his *De Revolutionibus Orbium Coelestium* in 1543 (conveniently immediately post mortem).

Galileo Galilei (1564–1642) — the great Italian natural philosopher and mathematician — moved science into a modem era. He must be given the credit for establishing physical science and astronomy as fundamental disciplines. He established mathematics as the language of science: a language that would be embellished by Descartes and Newton. It was adoption of mathematics that gave a quantitative component to science, leading to the formulation of "Laws" that would, through Newton and Einstein, led to an encapsulation in mathematical formulæ of the properties of the cosmos. His studies of inertia, the law of falling bodies, and parabolic trajectories began the study of motion upon which Newton would build.

Galileo's focus on experimentation was of great importance in the development of science. On hearing of the "telescope" in 1609, he grasped its significance, building his own overnight and immediately used it to conform the Copernican hypothesis of a heliocentric system. The magnification of twentyfold was significantly greater than earlier telescopes: he drew the phases and texture of the Moon, discovered four moons that revolved around Jupiter, and found many stars not previously recognised. He described the "ring" around Saturn, and showed that Venus went through phases similar to the Moon, more support for the idea of revolving around the Sun. These of course challenged the Aristotelian cosmology adopted by the Church: a corrupt Earth at the centre of a perfect unchanging heaven, i.e. he found: there was more than one centre of motion in the universe, an imperfect surface of the Moon, and the evidence that Venice rotated around the Sun — with significant consequences for Galileo (the beginning of tensions raised by unwanted science — nothing has changed). Galileo stands at the centre of astronomy and classical physics using the "new mathematical language" to create the first great laws that describe the cosmos.

Two astronomers did much to set a scene for Galileo: Tycho Brahe (1546–1601) and Johannes Kepler (1574–1630). Brahe was a Danish astronomer who did much to map celestial events and stars before the telescope became available, using an armillary sphere to locate positions. He would establish positions for over 1000 stars. Kepler joined Tycho, and would use Tycho's tables to comprise his own, which became a basis for determining longitude. Perhaps Kepler's main discovery was his three laws of planetary motion, extending the Sun-centred solar system of Copernicus into a dynamic universe with the Sun constraining planets around in noncircular orbits. Kepler used Euclidian geometry of polyhedrons by relating orbits of the known planets, to support his idea that he could discover the architecture of the universe. He postulated that a single force from the Sun accounted for the increasingly long periods of motion as the planetary distances increase. Reading Gilbert's *De Magnete* identifying "the great magnet, the Earth," he adopted magnetism as that great force: correlating inversely with distance of the planetary orbits.

Isaac Newton (1643–1727), born in the year of Galileo's death, was the right person, in the right place, at the right time to formulate the laws of classical physics, building on the ideas and discoveries of the scientific revolution over the preceding century. In essence, he developed Galileo's idea of a mathematical science of motion and his "new mechanics" built on the idea of inertia. Descartes, Galileo and Kepler had challenged the qualitative geocentric views of Aristotle — so firmly held within the environments of Oxford and Cambridge — and set forth a physical reality composed entirely of particles of matter in motion and held that all the phenomena of nature and the cosmos result from mechanical interaction.

Newton was aware of Gassendi's revival of atomism, which allowed voids which would become important in Newton's analysis of the cosmos, while Robert Boyle's early studies on the nature of matter influenced Newton's views on chemistry. He developed mathematical skills building on Descartes' *La Géométrie* and the use of algebraic methods to analyse problems of geometry. He discovered the binomial theorem and developed the calculus as a tool employing infinitesimal considerations to find the slopes of curves and areas under curves. And this was largely before he received his bachelor's degree!

He studied the elements of circular motion, applying the analysis to the Moon and the planets, and derived the inverse square law that gravity decreases with the square of the distance of the planet from the Sun: an observation crucial to his law of universal gravitation. He made important contributions to the physics of light but, being fixed to a mechanical view of the cosmos, saw light (and electrostatic electricity) as yet another form of particulate physics. Newton's analysis of motion and gravity published in his *Principia* by quantifying the concept of force completed an analysis of quantitative mechanics that became the centrepiece of natural science with his three laws of motion. Then he derived his law of universal gravitation, relevant to Earth and the cosmos.

Published in 1686, his monumental *Principia* became the fundamental basis of modern science: embracing the principle of inertia (First Law); a quantitative statement of the action of forces on bodies he had at the centre of his construct of nature (Second Law); and for every action there is an equal and opposite reaction (Third Law). Circular motion could be analysed in terms of these laws. Substituting his formula into Kepler's Third Law, he found the centripetal force holding planets in their orbits around the Sun, decreased with the square of the planet's distance from the Sun; similar calculations applied for moons in relation to their planets. He concluded a generic force existed, and with the measured acceleration of gravity on the Earth's surface, he concluded "the law of universal gravity" (which he could apply to orbits, tides, comets etc.), i.e. all particles attract with a force proportional to the product of their masses, and inversely proportional to the square of their distance of separation. The impact of Newton's *Principia* was immediate and dramatic: for a generation the few paid positions for scientists (the chairs at Oxford, Cambridge and Gresham) were filled with young Newtonians.

We must not forget that Newton made important discoveries regarding light. Light had been a focal point of the Scientific Revolution from the time of Kepler's *Paralipomena* (1604). Descartes' law of refraction added a mathematical analysis of light transmission and was used by Newton as another example of mathematical regularity of the universe, though he was wedded to the mechanical idea that light consists of motion transmitted through a medium, i.e. there was no void. Newton accepted this mechanical view of light and supported the atomistic idea of corpuscles in motion. Newton's contribution was a denial that light was homogeneous, but rather a mixture and that the colour spectrum reflects the components of "white light." Based on this idea, he reasoned that chromatic aberration could not be eliminated, so he invented the reflecting telescope.

The turning point in the study of light came with the Dutch scientist (who worked in Paris) Christian Huygens, who developed the idea of wave theory to account for the laws of geometric optics in 1678: "every point on a wave front may be considered a source of secondary spherical wavelets which spread out in the forward direction at the speed of light." This began a period of 350 years' research, culminating in the wave-particle duality to light and the Quantum Theory of Planck and Einstein (i.e. light and matter consists of particles with wave-like properties: light particles are photons, and matter particles are atoms).

This brings us to James Maxwell, who was to waveform propagation of energy as Newton was to particle physics. He developed laws of EMR critical to the physics of late 19th century. To understand the importance of Maxwell to the history of physics, first let us look at how EMR is seen today and examine the historic steps that followed Maxwell's equations of 1862–1864.

Today we understand EMR as waves or particles (quanta, photons) propagated through space with electromagnetic and radiant energy. These waves are synchronous oscillations of electrical and magnetic fields that propagate at speeds of light. In media, the oscillations of the two fields are perpendicular to each other and to the direction of energy and wave propagation, i.e. the wave front is a sphere. EMR is derived from electrically charged particles and has properties of energy, momentum and angular momentum (and can impart energy to matter it meets).

Maxwell derived the laws and equations that established modern views on EMR by formulating the classical theory of EMR, bringing together electricity, magnetism and light as different manifestations of the same phenomenon. The speed of the waves that was predicted was that of light. This had been calculated by Romer in 1676, by using the time gap in observing periods of Jupiter's moons depending on how close the Earth was to Jupiter.[4] He calculated 22 minutes for light to cross the Earth's orbit, and Huygens combined this with an estimate of this diameter, to calculate the speed at 220,000 km per second (25% less than the actual). The electromagnetic spectrum of Maxwell was that of light. Expansion came through the 19th century. In 1800, Herschel refracted light through a prism and noted that an "invisible" band beyond red could induce heat: he called these 'caloric rays," which we now know as infrared rays. The next year Ritter, using a similar system, noted that an invisible band adjoining violet at the other end of the solar spectrum darkened a silver chloride plate (the beginnings of photography). This was ultraviolet light. Then Maxwell and his equations (1862–1864). In 1887, Hertz used electric circuits to produce low-frequency oscillations (radio waves) with recipes from Maxwell.

The next series of components of the EM spectrum came from the discoveries of atomic physics at the end of the 19th century. In 1895, Wilhelm Röntgen produced and detected EMR of short wavelength, called X-rays. He passed a high-voltage current through a vacuum tube, and noted radiation produced passed through a barrier to detect fluorescence on an adjoining screen. He called these "cathode rays" in experiments that began dissection of the atom: it won for him the first Nobel Prize in Physics in 1901. The following year, Henri Becquerel observed penetrating radiation from a natural substance, uranium, via development of an image on a protected photographic plate. Radioactivity had been discovered, and another Nobel Prize awarded (actually, part of a long line of nuclear physicists over the early decades of the 20th century). This was followed by the studies of Marie Curie showing only certain elements (in particular, polonium and radium) were "radioactive," and she and her husband shared the Nobel Prize in 1903 with Becquerel. Ernest Rutherford at the Cavendish studied pitchblende (uranium oxide) to identify two charged particles alpha and beta forms of radiation

4 See Spence JCH (2019) Speed limit: how the search for an absolute frame of reference in the Universe led to Einstein's equation $E = mc^2$ — a history of measurements of the speed of light. *Journal & Proceedings of the Royal Society of NSW* 152: 216–241. [Ed.]

(helium nuclei and electrons respectively). In 1900, Paul Villard identified a neutral and penetrating radiation, which would become known as gamma rays, named by Rutherford. In 1910, William Bragg showed that gamma radiation is a short wavelength component of the electromagnetic spectrum. In 1914, it was Rutherford again who placed gamma rays in the appropriate slot in the electromagnetic spectrum.

Here we have traced the development of physics through the contributions of three great minds: Galileo, Newton, and Maxwell. Each evolved the language of mathematics to classical physics to reduce the world — indeed the cosmos — to a series of equations that defined pathways for other scientists. Galileo and Newton developed the laws of mechanics and classical physics, while Maxwell brought electricity, light and magnetism together as related wave forms. The late 1890s introduced atomic physics and the laws of Newton were found wanting. Planck initiated the new era by developing quantum mechanics, combining the essential features of Newton and Maxwell (particulate and wave form) into a single entity at a time before atomic structure was understood, and when Newtonian laws failed to explain energy and discrepancies based on release of energy in quanta from black bodies energised by light. He derived the Planck constant, which links the amount of energy of a photon with the frequency of its electromagnetic wave ($E = hv$).

By the early 1900s, a crude model for the atom was taking shape, and in what can only be called "Einstein's year of 1905," Einstein used the quantum theory to explain the photoelectric effect i.e. light exists as packets (or photons) that can knock out electrons in a metal in a precise way, accounting for energy emission only in discrete quanta. For this he was awarded the Nobel Prize (1921). In 1905 (aged 26 and working in a Swiss patent office), he published the first proof of atoms by observing Brownian movement, he developed Special Relativity as a law of nature: the laws of physics are invariant in all inertial systems. It is about the relationship between space and time. The speed of light is the same for all observers. The famous equation $E = mc^2$, where energy and mass are the same, is an outcome of this law. This theory was limited to non-accelerating observers. Ten years later, he published his general theory of relativity. In his special theory, he had shown space and time are woven into a single continuum known as space-time. Then he determined that massive objects cause a distortion of space-time (a "gravity" effect or "warping" effect). This has been proved by "gravitational lensing" or the bending of light around a massive object (e.g. black-holes), quasars around galaxies, the red-shift phenomenon, and gravitational waves.

The excitement of tracing the great "laws" that define the physical universe, from the ideas of Galileo to those of Einstein, must not detract from the mundane (and understandable). First amongst those who followed Newton was the great French physicist-mathematician, Pierre-Simon Laplace (1749–1827). A worthy successor of Galileo's, he translated the geometric study of classical mechanics to one based on calculus, while along the way he contributed to expanding knowledge in areas ranging from the nebula theory of the origin of the solar system, the existence of black holes and gravitational collapse, to numerous contributions in classical physics including heat, a dynamic theory of tides, spherical harmonics, to name a few. His monumental *Celestial Mechanics* (1799–1825) in 5 volumes, was a statement of the current state of physics. Rightly, Laplace was known as the "French Newton."

The second "window" in the period 1700–1900 was a junction point between classical physics, astronomy and the new science of electromagnetic spectrum. Newton had discovered that prisms could disassemble and reassemble white light, but it was the Germans in Heidelberg, Robert Bunsen and Gustav Kirchhoff, who developed the spectroscope that could identify materials that emit light when heated. They used this technology to discover two alkali group metals, caesium and rubidium.

This technique was immediately adapted to astronomy, when identification of elements and chemical processes led to our current understanding of nuclear-powered stars, the sequence of evolution of elements within stars by addition of helium in a process known as nuclear fusion. Only stars as large (or larger) than our Sun can create elements larger than helium. All the atoms in the universe began as hydrogen, and evolve via helium by the process of nucleosynthesis, or atomic fusion. Spectroscopy was used by Edwin Hubble (1889–1953) to determine the presence of other galaxies, and, in 1929, he showed these distant galaxies were expanding by showing that light emanating from the galaxies was "stretched," with an increase in wavelength, causing a "red shift" in the light spectrum. The idea of the "Big Bang" theory of the origin of the universe followed.

Chemistry (or the "composition, properties and reactivity of matter")

The French philosopher, mathematician and astronomer Pierre Gassendi (1592–1655) kick-started "modern" chemistry by championing an old idea of "atomism" as the basis of matter: he promoted the idea of particles characteristic of a particular substance as the basis of matter, bouncing around in a void. This at a time when his influential compatriot René Descartes denied the existence of a void, an idea that already has been shown to retard scientific progress. The wealthy Anglo-Irishman Robert Boyle (1627–1691) can be credited with the beginnings of scientific chemistry and separating it (at least to an extent) from its precedent, alchemy, with his publication in 1661, *The Sceptical Chymist*. In this book he described Boyle's law and the "spring in the air" relating pressure to volume of an enclosed gas. He explained these observations with a hypothesis of a "universal corpuscular theory." His studies on air went to its capacity to support combustion and life.

There followed a century when physics would thrive, culminating in Newton describing an ordered world and universe in mathematical terms, inspiring other scientific disciplines to create their own unifying principle on one hand, while on the other combining with humanists and philosophers such as Voltaire to create a rationalism and hope for a better life for the individual, in a movement that became known as The Enlightenment. The practical outcomes of physical science made possible the Industrial Revolution (1740–1780), which in turn encouraged greater scientific endeavour, especially in those areas relevant to the new industrial age: heat, steam and gases. The yawning time gap from Boyle's publication in 1661 (especially when one notes the advances in physics) was simply due to there not being available the "tools" to create a steady heat source (to drive chemical reactions) and methods to accurately measure the components and outcomes of reactions.

The era of modem chemistry began with Joseph Black (1728–1799), a Scottish physician-chemist who used the technology of the Industrial Revolution to accurately measure the "ins and outs" of chemical reactions. He would show air is a mixture by identifying carbon dioxide as "fixed air" (produced by treating "mild alkali" with heat and acid). His instrument maker and colleague in studies of latent heat was a young James Watt, who would later transform the primitive steam engine of Thomas Newcomen (used in 1712 to pump water from a coal mine) into a series of efficient engines by using a second cylinder as a condenser to minimise heat loss and increase efficiency. (He would go on to make many improvements and develop a profitable business in Birmingham with Boulton. In Birmingham, he joined with Erasmus Darwin, Josiah Wedgwood and Joseph Priestly to form the "Lunar Club.") There followed important studies identifying oxygen, hydrogen, nitrogen and their properties by Joseph Priestly and Henry Cavendish, again through remarkably accurate instrumentation. Cavendish (1731–1810), after his discovery of hydrogen as "flammable air," showed hydrogen and oxygen in a ratio of 2:1 in the composition of water. Cavendish, considered to be the outstanding English chemist of the 18th century, used a clever method with a torsion balance to determine the density (and therefore weight) of the Earth.

His descendant Thomas Cavendish would finance the Cavendish Laboratory in Cambridge in the 1870s, a mecca for the revolution in science where the composition of the atom was discovered (and where many Australians gained their scientific training). Cavendish was an early subscriber to the Royal Institution, where Humphry Davy would continue study of elements and Michael Faraday would begin study of electromagnetism and its contribution to the industrial revolution. Cavendish was the end of a series of English 18th century chemists — Black, Priestly and Cavendish — who developed sensitive quantitation into laboratory practice to analyse the constituents of air and water, and to begin analysis of heat and energy transfer in combustion. The way was prepared for Antoine-Laurent Lavoisier (1743–1794).

Lavoisier, considered "the father of modern chemistry," was a bon vivant aristocrat whose day job as a tax collector ended at the guillotine.[5] His wealth was used to construct the best equipped laboratory in Europe and he followed closely on recent British experience in attention to detail, and careful measurement in the analyses of chemical reactions. He complemented and completed the work on analysis of air by British chemists, and built on these successes to examine the processes of combustion, respiration and calcination. He studied the idea of Stahl, known as the Phlogiston Theory: that heating matter released "phlogiston" which re-entered on cooling. Careful collecting and weighting all components of the reaction denied the Phlogiston Theory and along the way led to the "law of conservation of mass." He showed both respiration and combustion were processes of oxygenation (as was calcination). In his attempt to establish chemistry on a scientific basis, he published in 1789 a list of elements. Of his

5 He stayed in Paris despite being urged by Joseph Priestly to quit France. [Ed.]

33 entries, 23 remain recognised as elements (including recent discoveries manganese, molybdenum and tungsten). Lacking was structure. Modern chemistry is so closely connected to the Periodic Table, and Lavoisier's first attempt began a process which continues. An overview of how the table evolved gives insight into chemistry post-Lavoisier.

In the year of Lavoisier's execution, Joseph Proust extended the idea of conservation of mass, to the law of definite proportions, i.e. the ratio of the elements in a compound by weight are always the same. It was John Dalton (1766–1844) across the channel who showed these ratios were always small whole numbers. He concluded that each element was composed of minute indivisible particles; the atomic theory was taking shape. To give a mathematic base, Dalton composed a table of atomic weights, giving hydrogen the reference number of one. This became the Law of Multiple Proportion (1803). Jacob Berzelius developed the shorthand still used today in for chemical compounds. There followed discovery of many new elements: Davey by electroanalysis (sodium, potassium, magnesium, calcium, strontium, barium, boron, and chlorine). In 1829, Johann Dobereiner (in Germany) noticed similarities and groupings (alkali metals, alkaline earths and halogens) and others: all in groups of three, with the middle element of each having a weight of the average of the others. This became "the law of triads." A pattern loomed. In 1864, John Newlands, a British chemist, published the "law of octaves," extending the idea of groupings (just short of a "Periodic Table").

The pattern we now recognise as the Periodic Table was put together by the Russian chemist Dmitri Mendeleev in 1869. He arranged the 63 known elements according to their atomic weights in "suits" determined by shared properties. Where needed to make the pattern work, he left gaps, but by doing this predicted properties of to-be-discovered elements. The stage was now set for the study of atoms themselves: this came in a rush after Becquerel discovered radioactivity in 1896, and Thompson at the Cavendish Institute showed "cathode rays" emitted into a vacuum by a negative electrode were electronically charged particles that weighed less than an atom. In 1900, Becquerel showed his beta particles were the same as Thompson's cathode rays. The atom was being "broken down" and studied. Seven years later ,Rutherford demonstrated that alpha particles were helium ions. Then came arguably the most important experiment in modem science: between 1908 and 1910, Rutherford fired particles at gold foil. Most passed through, some were deflected, but a very few bounced back. On this, he based his model for the atom: a central positively charged nucleus, surrounded by electrons. Losing alpha and beta particles changed atoms, and new members for the Periodic Table were soon identified: the first being polonium and radium in 1898 by Marie and Pierre Curie.

Earth sciences

The western take on earth sciences considers discovery of the Earth's surface, and the Earth itself. For 1500 years the mapping of the Earth's surface was contained in 10,000 coordinates listed by Claudius Ptolemy. Scientific mapping began with the first accurate and detailed map of the known world up until the mid-15th century and drawn by the Venetian monk Fra Mauro. The map is two square metres and took several years to complete. It sits squarely in that interval period between bible-based geography and scientific cartography. It is flanked by Ptolemaic ideas and the garden of Eden, yet the map itself includes what is known without the guesswork of earlier maps. One hundred years later, expeditions in search of the luxury goods market in the east had changed western knowledge of the world dramatically: the New World had been discovered and a continuous ocean around the world had been explored.

Gerardus Mercator (1512–1594), a Dutch cartographer and geographer, produced in 1569 the most scientifically accurate map to that time, using a new projection allowing sailing courses of constant direction. His academic interests in mathematics, geography, astronomy and geomagnetism anticipated the development of "navigation physical sciences" over the next 300 years. The interest in cosmography by these early cartographers, as seen in their globes and celestial atlases, underpins the relevance of navigation using star charts, and the interest and relevance of the physical sciences to accurate and safe maritime travel.

The science of geology was more recent. At the end of the 18th century the main point of discussion was argument between two groups: the *neptunists* and the *plutonists*. The first were those who believed the world as we know it followed a liquid inundation, with precipitation from these seas of land forms including basalts and igneous rocks. These neptunists were led by a German, Abraham Werner, who was the authority on mining and mineralogy, and a powerful influence across Europe.

Biblical mysticism was slow to change. Buffon (whom we have met before) suggested a role for heat in creating some strata. James Hutton expanded these ideas, developing the concept of volcanic rocks undergoing erosion over great time periods, forming sediments: his followers were called plutonists. This idea of natural processes occurring over huge time periods shaping the Earth's crusts was called uniformitarianism, and it became a basic tenet of the new science of Hutton's carefully argued views of continuous process of erosion, deposition and uplift. It was first published in 1785, leading to intense interest in the stratigraphic column.

William Smith travelled Britain during the course of his job as a canal surveyor, and noted the value of identifying strata according to their fossil content. In 1815, he published the first geological map of Great Britain. In France, the comparative anatomist Cuvier realised that the relative age of fossils could be determined by the strata sequence in the Paris basin, published in 1811. Definition of the stratigraphic sequence became the main game: Adam Sedgwick mapped strata in Wales as Cambrian, while Charles Lyell was postulating a subdivision of the Tertiary Period. Roderick Murchison determined the upper parts of Sedgwick's Cambrian series as the lower parts of the Silurian Period. As the stratigraphic sequence developed in Britain, similar findings were made globally. In 1830, Charles Lyell published the first volume of his foundation treatise-on modern geology, *Principles of Geology*, giving substantive proof of Hutton's theory from across Europe, strongly supporting Hutton's concept of a gradual and continuous change. Lyell's views on great time periods for change had an impact on a young Charles Darwin and became an important argument in his theory of evolution.

At the turn of the century, Arthur Holmes developed radiometric dating of minerals. His method was based on uranium-lead radiometric dating, where the amount of lead represents a decay product from traces of uranium incorporated when the rock was formed. In 1912, Alfred Wegener, a German geophysicist, became known for his theory of continental drift. He postulated an early continent, Pangaea, that broke up, with segments migrating to positions we recognise today. Though controversial at the time, as no mechanism was known, Holmes suggested the Earth's mantle contained convection cells involving heat from radioactive decay, moving segments of crust at the surface: this became a model for seafloor spreading and plate tectonics.

Much of the above traces contributions by British geologists, but continuous and important studies on the age of the Earth (Comte de Buffon), volcanic rock and geological mapping (Jean Guettard) and the foundation of volcanic geology and the origin of basalt (Nicholas Desmarest) in the 18th century, established a grand tradition for French geology.

Development of a structure for science

An important component in the development of western science was its organisational basis. From around 1500, science in Italy was centred on the traditional universities of the city states, with any institutional attempt such as the Accademia del Cimento, established in Florence by Borelli and Malpighi in 1657, lacking formal structure and durability. The 17th century, however, was a time where the empiricism of science combined with the humanism of the renaissance and the importance of the individual that flowed from the destruction of the Black Death and the severing of church control that came from the reformation, to crystallise as the Enlightenment. Informal discussions led by new-breed philosophers in the salons of Paris (and similar in England) were matched by gatherings of wealthy natural philosophers in London and Paris. One such group informally met at Gresham College (London), and led by Robert Boyle and Christopher Wren, formed the Royal Society in 1660, with a focus on experimentation. Publications such as Hooke's *Micrographia* and Boyle's *Skeptical Chymist*, then the *Philosophical Transactions* as a regular science bulletin from 1615, established an international credibility attracting scientists such as Malpighi (Italy) and Huygens (Holland).

French science polarised around the Academie de Science, founded by Corbet on behalf of Louis XIV in 1666, and with the King's financial support. It re-emerged after the revolution in 1795 as part of a "collective" of institutes, playing key roles in contemporary debates such as whether light was a wave form or particulate, and a connection with the great voyages of exploration and science.

However, funding of science was deficient and new initiatives were needed. In England the Royal Institution was begun in 1799 by wealthy benefactors to introduce new technologies in the age of the Industrial Revolution and to "translate" science for the public. Research followed with an extraordinary line of scientists: Humphry Davy, Michael Faraday, the Braggs (Australians), to name a few. The idea of pure research institutes began with the Cavendish Laboratory in Cambridge in 1874 led by James Maxwell (electromagnetic theory), JJ Thompson (the electron), Ernest Rutherford (structure of the nucleus), and Lawrence Bragg (whose introduction and crystallography into the Cavendish led to Crick and Watson describing the DNA double helix). The Cavendish, together with scholarship funding through the legacy of the 1851 Exhibition Fund,[6] enabled a strong training programme for Australians.

Highlights of our tour will be visits to all these institutions in Paris, London, and Cambridge, with private showings of documents and publications from their libraries and archives.

Discussion

In this brief "Big Science" overview of western science, identifying "moments" that reflect progress in understanding science-based knowledge over 500 years, I have attempted to give a sense of logic and organisation to key ideas and events that have (in a staggering way) led to where we sit today. With the entwined development of technology, we can map our genome overnight for a few hundred dollars, collection information from the edge of our expanding universe that tells us of its beginning (by analysing data equivalent to every word ever spoken — everyday!), we can be confused about illogical ideas such as space-time and energy/mass equivalence (as well probe the depths of subatomic particles — or should we say waves?), and finding plant and animal fossils (and coal) in Antarctica no longer surprises us (as we know about plate tectonics — don't we?). Perhaps at a personal level, it is harder to accept the linearity of our relationship with sludge, but then we can accept that going back a bit, we have an ancestral relationship with hydrogen and helium produced in stars through nuclear fusion (or nucleosynthesis). We have come a long way! In putting together this "discovery grid," I was reminded of my boring high-school science curriculum: why was I never made aware that these topics were the windows on discoveries upon which our modem life is built?

Looking at the four "streams" of Big Science (artificial though this may be), a number of points need to be made.

First, there is a "beginning" for each clouded in an immediate past of mythology, and a direct outcome of the Renaissance where society is being re-shaped by reflecting on past glories and present scepticism. The three regions we visit (Northern Italy, France, and England) cover all but one of these pathfinders. All were exposed to the arguments of empiricism and rational thought, be it within the great universities embedded in the Renaissance, or influenced by a new breed of philosophers claiming Bacon and Descartes as members.

Second, it is interesting to note that most of those who worked in science prior to 1900 were wealthy and for whom science was an absorbing hobby. Over 40 per cent of those identified had medical training, while others worked within the comfort zone of the church. Universities were few, but those who had university training included advanced mathematics. Scientific societies began to appear in the second half of the 17th century; largely through these (and privately published books), discoveries were announced. In the 19th century, research institutions appeared: the Royal Institution (1799) in London and the Cavendish Laboratory (1874) in Cambridge became of central importance to scientific discovery

6 This fund also supported the only NSW-born Nobel Laureate, "Kappa" Cornforth and his wife, in their UK studies. [Ed.]

(and each relevant to Australia). The development of institutes dedicated to science became of central importance to the way scientific structures developed in Australia. The "English-Australian Shuttle" in the 50 years from 1880 was an outstanding success for all involved.

Third, examination of the various streams identifies the "big" ideas: in biology, structure-function relationships are followed by Darwin's evolution, and the relationship between genes and environment with Crick and Watson's structure for DNA in 1953, closing the evolution-genetic loop. The second stream of classical physics runs alongside "Laws" which progressively explains the physical world — and cosmos — in terms of mathematical formulæ. Galileo and Newton are followed by Maxwell, whose focus on the electromagnetic spectrum shifts interest from particulate matter to wave forms, while Einstein accepts the incongruities of particles and waves being the same: mass is energy and the speed of light is a constant in his relativity equations. All of this leaves us with $E = mc^2$, the good and the bad!

The third stream of astronomy can't be removed from physics and mathematics; indeed it is the discovery of lines in an excited electromagnetic spectrum as being diagnostic of elements that transformed an astronomy that could use these tools to identify the origins and constitution of the universe through analysis of nucleosynthesis and an expanding universe, when proving Einstein's General Relativity by demonstrating the warping of light from peripheral pulsars.

The fourth stream, chemistry, is a late bloomer, as the tools needed were not available. An intriguing web was constructed based on accurate measurement and the search for patterns, all concentrated on the work of Lavoisier in Paris in mid-18th century. The accidental discovery of X-rays and spontaneous radiation at the end of the 19th century created an opportunity to prise open the atom, done superbly by the New Zealander Ernest Rutherford. The final stream was Earth itself: first to map its surface and then to understand the processes that have created both landforms and seabeds. The great understanding — so simple today — was the insight of Hutton into the continuous processes of erosion and deposition over huge time frames. The other great insight came from Wagener in the early 20th century, when he concluded his theory of continental drift; 50 years later, plate tectonics and the mechanistic questions were answered.

Finally, the tour "Padua to London" has been designed to capture most of these great moments, to visit where discoveries were made, and get some sense of the impact made on contemporary science. We have the opportunity to see how western science was a product of the Renaissance, yet became a central tool of the Enlightenment that followed, to shape the world we live in. We will see how technology and science converge to mutual benefit, how the study of matter, be it physics or chemistry, converges at a subatomic level, and biology. New focuses on DNA sequences and astronomy use all the lessons from physics and chemistry to better understand an infinite universe. Study of earth dynamics has found its underpinning principle in plate tectonics, and all the technology developed probes deeper in the Earth as it reaches to the edge of the universe.

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Thesis abstract

Promoting quality teaching in Albanian schools: where political history and pedagogy meet

Julie Cowan

Abstract of a thesis for a Doctorate of Philosophy submitted to
The University of Newcastle, Callaghan, Australia

Since its dramatic exit from communist rule in 1991, Albania has faced multiple policy reforms aimed at modernising its education system. These reforms are driven by two social imaginaries informed by global movements in education — Albania's imagined Europe and the OECD's globally competent learner. The goal is to improve the quality of classroom practice and harmonise the standard of initial teacher education (ITE) with programs provided in Europe more widely. Despite adopting a 'learner-centred' approach to teaching, little change is evident in the quality of instruction in Albanian classrooms. Studies show that teachers remain chiefly tied to direct textbook instruction, unable to move far from the confines of the traditional teacher-led practices they experienced during their own schooling and throughout their teacher education. Thus, ITE remains a key national priority for improving the quality of teaching and learning in today's classrooms. With Albania's aspirations to emulate more developed parts of the world, this study adds to the literature on the dominant neoliberal discourse of globalisation and its effects on education policy development in non-Western contexts. While addressing the restrictive effects of globalisation on teaching quality in Albania, my multi-phase mixed methods study first explores Albanian ITE by analysing Master of Teaching curricula from three Albanian universities. Next, the study explores the potential value of the NSW Quality Teaching (QT) Model as a tool in developing teachers' agentic capacities to continually improve the quality of their practice. Favouring an anti-dualist ontology, the study is anchored in Deweyan transactional realism and utilises an ecological approach to teacher agency as a lens through which the temporal-relational aspects of participants' experiences were viewed. Stakeholders at three different levels of Albanian ITE — namely, teacher-interns (n = 20) who had completed their Professional/Scientific Master of Teaching qualification; ITE students (n = 6); and teacher educators/policy experts (n = 7) — were introduced to the QT Model through professional development (PD) workshops. While the PD enabled practical engagement with the Model and the associated process of lesson coding, the teacher-interns also experimented with the Model and coding in their own classrooms, thus providing real-world insight into the Model's utility. To identify changes in teaching quality, quantitative data were generated by coding pre- and post-lesson observations using the QT Model's coding scales. Qualitative data, elicited through document analysis, participant interviews, and personal field notes, provided contextual insights on Albanian ITE as well as participants' perceptions of the QT Model and associated coding. Together, these data demonstrate an uneven and generally weak pedagogical foundation laid by Albanian ITE, leaving pre-certified teachers without the means to produce the quality of teaching sought by the government. Responses to the QT Model and coding process were overwhelmingly positive, and the lesson observations indicate clear potential for direct, beneficial impact on the quality of classroom practice. Additionally, when teachers engage with QT PD by systematically reflecting *on*, *in*, and *for* practice, they build agentic capacity for ongoing pedagogical development. These results highlight the value of addressing teaching quality by investing in both teachers' general pedagogical knowledge and their analytical skills. With an ardent focus on teaching methodology informed by neoliberalism, I argue that Albania's attempt to emulate other nations in pursuit of its imagined future has not demonstrated, and is unlikely to demonstrate, the desired educational outcomes it seeks. Rather, the government's current approach restricts teaching quality and the development of teachers' agentic capacity to the point that, if not addressed, the quality of classroom practice in Albania will continue to suffer. While there are no easy fixes, I contend that taking a holistic pedagogical approach rather than a technical-methodological approach to improving teaching practice is essential if quality teaching is to be attended to within the Albanian context.

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Thesis abstract

Divergent synthesis of heterocycles using dinitrobenzyl chloride analogues

Lillian Anne De Ceuninck Van Capelle

Abstract of a thesis for a Doctorate of Philosophy submitted to the University of Wollongong, Australia

Often prized for their bioactivity, heterocycles are present throughout chemical industries and research. The development of new heterocycles and novel methods to synthesise them are central pursuits of small-molecule chemistry and serve as the overarching ambition of this thesis. The following dissertation is divided into two parts, detailing the alternate reactivity of electron-deficient di-substituted benzyl chloride analogues and the synthetic utility of their respective heterocyclic products.

Part I exploits the electrophilic reactivity of 3,5-dinitrobenzyl chloride in a multi-step process to synthesise benzoazepine-fused isoindole atropisomers. Recent developments in the study and synthesis of medium-ring benzo-fused N-heterocycles are reviewed in Chapter 1. The protocol developed for the synthesis of atropo-enantiomeric benzoazepine-fused isoindoles is detailed in Chapter 2. Based on previous work by our research group, 2-aminobenzaldehydes are benzylated with 3,5-dinitrobenzyl chloride to generate a tethered species which can form azomethine ylides *in situ* that undergo an intramolecular (3 + 2) cycloaddition-elimination sequence to benzoazepine-fused isoindolines. In this work, a procedure to oxidise the isoindoline systems to the respective isoindoles is developed, provoking dramatic conformational changes and enantio-atropisomerism. Through kinetic HPLC experiments and X-ray crystal structure analysis, the source of this atropisomerism and the relative enantiostability of analogous compounds was determined, with restricted rotation around the C_{aryl}–$N_{sulfonamide}$ axis identified as a key factor in regulating the rate of racemisation. In Chapter 3, this work is extended to atropo-diastereomeric systems through the addition of a pendent stereocentre, installed during formation of the azomethine ylide. With the diastereomers distinguishable using NMR spectroscopy, oxidation of the isoindolines was revealed as a stereoselective process dictated by central-to-axial chirality conversion. Further, the folded conformation of the oxidised system was shown to induce facial selectivity during Diels–Alder cycloaddition of the isoindole. This process thus allows for the selective generation of complex three-dimensional structures in high yields.

Part II of this thesis discusses the bifunctional reactivity of benzyl chlorides substituted with electron-withdrawing groups in the 2- and 4-positions. In addition to reacting as electrophiles, 2,4-substituted benzyl chlorides have been shown to undergo benzylic deprotonation to form a resonance and inductively stabilised anion, enabling them to function as carbene-like nucleophiles.

In Chapter 4, work is discussed where this dual reactivity is harnessed through the development of a two-step (4 + 1) annulation-dehydration protocol to synthesise C2-arylated indoles and benzofurans. Using 2,4-dinitrobenzyl chloride as a model, a substrate scope of the 4-atom component found that variation of the aryl substituents was broadly tolerated, with subsequent dehydration to the desired indole or benzofuran product proceeding smoothly (33–98% yield). A probe into the limitations of the benzyl chloride reagent revealed that the protocol proceeds successfully with different *para* electron-withdrawing substituents (18–77% yield). The singly-activated 2-nitrobenzyl chloride however, was not sufficiently nucleophilic to undergo (4 + 1) cycloaddition, instead participating in electrophilic benzylation. Side-products generated from 2,4-dinitrobenzyl chloride under the reaction conditions were also investigated, revealing multi-nitrated, ring-strained compounds of potential interest as high energy density materials.

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Thesis abstract

Understanding and preventing poor diet, alcohol use, tobacco smoking and vaping among adolescents from low socioeconomic and remoteness areas through eHealth interventions

Lyra Egan

Abstract of a thesis for a Doctorate of Philosophy submitted to the Faculty of Health and Medicine, The University of Sydney, Australia

Chronic diseases disproportionately affect disadvantaged populations, including individuals of low socioeconomic status (SES) and those living in geographically remote ('regional', 'rural', and 'remote') areas. These health inequities are systemic, unjust, and preventable. Adolescence represents a critical period for shaping future health behaviours and outcomes, offering a pivotal opportunity to mitigate the burden of chronic disease and reduce disparities. During this key developmental period, lifestyle risk behaviours such as poor diet, alcohol use, tobacco smoking, and vaping typically emerge. Evidence-based prevention strategies during adolescence are essential to prevent the entrenchment and progression of these lifestyle risk behaviours into adulthood, thereby addressing the widening health equity gap faced by disadvantaged populations. This thesis aims to address critical gaps in the literature concerning lifestyle risk behaviours among adolescents from low SES and geographically remote contexts, with a primary focus on Australian adolescents. It also contributes to the global evidence base by offering strategies for the development of effective and equitable lifestyle behaviour interventions in both the Australian and international context. Chapter 2 of this thesis examines the prevalence of poor diet, alcohol use, tobacco smoking, and vaping behaviours across a large and geographically diverse sample of 4,445 Australian adolescents aged 14–17 years. The findings reported a nuanced and complex picture of these behaviours, showing that there are no uniform patterns of these behaviours across SES and geographical locations. Lower SES adolescents reported less excessive discretionary food intake and alcohol consumption compared to their mid-to-high SES peers. In contrast, regional adolescents fared considerably worse across alcohol and tobacco outcomes compared to their peers in major cities. Chapter 3 systematically synthesised the existing global evidence on electronic health (eHealth) interventions targeting poor dietary habits, alcohol use, tobacco smoking, and vaping among disadvantaged adolescents. The findings support eHealth interventions in improving dietary habits and reducing alcohol use among disadvantaged adolescents, but lacked evidence for addressing tobacco smoking, and vaping. Chapter 4 applied latent growth curve modelling to evaluate the moderating effects of SES and geographical location, on the efficacy of a universal eHealth, school-based intervention,

Health4Life, in targeting poor diet, alcohol use, tobacco smoking, behavioural intentions (diet-, alcohol-, and tobacco-related), psychological distress and knowledge over 24 months. There was little evidence of a moderation effect on most outcomes, with the exception of diet-related outcomes by geographical location. Adolescents in regional areas in the intervention group reported poorer dietary habits than the control group, whereas adolescents in major cities in the intervention group reported greater intentions to swap sugar-sweetened-beverages for water than the control group. Chapter 5 conducted a process evaluation of *Health4Life* among disadvantaged adolescents and their teachers to gain insights into the feasibility and acceptability of the intervention in disadvantaged schools. The findings revealed that content and technical challenges were key barriers to acceptability among disadvantaged adolescents, with participants identifying areas for refinement. Lastly, Chapter 6 evaluated the acceptability, and potential global scalability, of an effective eHealth school-based alcohol use prevention program, the *OurFutures Alcohol Module*, among disadvantaged adolescents in Bogotá, Colombia. The results support that with appropriate place-based end-user involvement in co-designing the adaptation, the *OurFutures Alcohol Module* could be an acceptable and engaging alcohol prevention program in Bogotá. This thesis outlines actionable recommendations for policy, public health, and research to support the development of more effective and equitable lifestyle behaviour interventions for disadvantaged youth. These insights have global implications for the design, implementation and scalability of such interventions. Applying these insights has the potential to improve chronic disease outcomes for disadvantaged adolescents on a global scale.

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Thesis abstract

Bridging the gap: A macro level approach to assessing and advancing the circular economy

Melissa Gutberlet

Abstract of a thesis for a Doctorate of Philosophy submitted to the Dept. of Applied Finance, Macquarie University, Australia

Circular economy is praised as a solution to the negative impacts of increased resource use. Although existing research has examined circular practices at micro and meso levels, there is a lack of comprehensive analyses that connect the levels and consider broader systemic impacts. As circularity is fundamentally a macro level phenomenon requiring coordination among various actors, there is a need for a better understanding of these interactions and more robust methods to evaluate and compare the diverse contributions to circular resource use. This dissertation addresses these gaps by exploring the following research question: How can circularity be assessed and advanced holistically?

After establishing the theoretical background of circular economy and related strategies (Chapter 2), this dissertation presents three chapters that form the basis of the main contribution to knowledge.

Chapter 3 uses National Business Systems (NBS) theory to explore how macro level factors and configurations affect the adoption of circular economy practices in different capitalist systems, with case studies from the United Kingdom (UK), Germany, and France. The analysis shows that the development and implementation of circular economy measures necessitate an encompassing consideration of the NBS in which they are embedded.

Building on the macro level conceptualisation, the question arises of how to assess, summarise and compare the different contribution of micro level actors. Chapter 4 explores the opportunities of machine learning (ML) to analyse these contributions by using nonfinancial disclosures. This chapter introduces a semi-supervised ML approach based on word embeddings and the Term Frequency-Inverse Document Frequency (TF-IDF) weighting scheme to reveal the intricacies of circular economy reporting.

Chapter 5 presents an empirical case study focusing on the automotive industry due to its reliance on virgin resources and vulnerability to supply chain disruptions. Using the semi-supervised ML approach, it analyses 406 sustainability reports from 32 car manufacturers between 1998 and 2023. It contributes methodologically by linking macro and micro levels of reporting and empirically by revealing industry progress in waste reduction and remanufacturing practices.

This dissertation advances theorisation of circular economy as a multilevel phenomenon and offers a methodology for assessing circularity that incorporates multiple levels of analysis. By shifting from micro and meso to the macro level, the dissertation enhances

theory development and understanding of the practice of circular economy's potential to reduce resource use.

This dissertation supports policymakers in more efficient policymaking and offers a method to assess policy implementation. For practitioners, it recommends adapting circular practices to macro level contexts and offers a tool to improve circular practices and reporting to align with evolving policies.

Limitations pertain to data quality in circular economy reporting and relatedly limitations of the ML model employed. Future research could address these issues by using primary data sources, exploring advanced ML techniques such as large language models (LLMs), and expanding the scope to different industries.

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Thesis abstract

Efficient control and simulation of quantum dynamics

Alexander Hahn

Abstract of a thesis for a Doctorate of Philosophy submitted to
The School of Physics, Macquarie University, Australia

Quantum simulation is one of the most promising potential applications of quantum technology. With the recent hardware developments in quantum computing, we are moving from a qualitative to a quantitative regime of quantum simulation, where even small errors can corrupt the scalability due to error accumulation. The origin of these errors is two-fold: on the hardware level, noise and decoherence disrupt the qubits; on the software level, quantum simulation algorithms are approximate implementations, introducing systematic errors to the computation. On the one hand, hardware noise can be effectively suppressed by the quantum control technique of dynamical decoupling. On the other hand, systematic simulation errors can be controlled through efficient implementations of the Trotter product formula. This thesis reports advances on both fronts by providing better characterisations of the errors in quantum simulation and dynamical decoupling.

In terms of simulation algorithms, we establish a better understanding of the simulation precision and more efficient ways to quantify it. This is related to the Trotter approximation error, for which we establish lower bounds as well as more effective upper bounds through an explicit dependency on the input state. Furthermore, we examine the procedure of discretising physical models to make them amenable for digital simulation before the background of the Trotter product formula and establish sufficient conditions for the validity of this approach.

Regarding dynamical decoupling, we quantify its efficiency when the system is coupled to a bosonic environment (e.g. thermal and pink noise). We also establish a unification result of dynamical decoupling with randomised kicks and the quantum Zeno effect, where the dynamics of a quantum system gets projected onto a subspace through frequent measurements. This allows us to find efficiency estimates for the randomised dynamical decoupling. Lastly, we develop a new dynamical decoupling scheme via generalised kicks through a quantum channel that acts on the environment. This scheme explicitly uses noise degrees of freedom and classical uncertainty to suppress environmentally induced errors.

The results in this thesis are based on studying the mathematical properties of quantum dynamics more broadly. To this end, we give a clear characterisation of the dynamics of mixed quantum states in the general setting of possibly infinite-dimensional Hilbert spaces. Furthermore, we establish a general method to obtain error/efficiency estimates for implementing quantum dynamics admitting physical symmetries characterised via Lie group representations.

Together, these results enhance both the accuracy and robustness of quantum simulations, potentially pushing the field closer to practical, large-scale applications.

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Thesis abstract

Molecular, morphological, and functional profiling of human astrocytes in stress-related psychiatric disorders

Dominic Kaul

Abstract of a thesis for a Doctorate of Philosophy submitted to the University of Wollongong, Australia

Severe stress is consistently one of the strongest risk factors for the development of psychiatric disorders, yet we still have a poor understanding of the cellular contributions to this risk in humans. Astrocytes are emergent players across brain functions, including regulation of the synaptic environment. However, the impact of stress on astrocytic functions, particularly in the context of human psychiatric disorders, is not yet well understood.

The primary goal of this thesis was to build a body of human-specific evidence on how astrocytes are shaped by stress at the cellular and molecular levels. This was conducted using a curated postmortem cohort consisting of psychiatric disorder cases stratified based on whether they had exposure to profound stress (deemed to have persisting ramifications) prior to diagnosis and at what life stage this primarily occurred. The work presented in Chapter 2 explores the transcriptome-wide changes underlying an association with a history of profound stress, using single-cell and spatial transcriptomics platforms to explore the transcriptional heterogeneity of cortical astrocytes. This approach highlighted that cortical astrocytes in the grey matter involved in synapse homeostasis particularly delineate the brains of people who lived with a psychiatric disorder and had a profound history of severe stress prior to diagnosis. This chapter also highlighted that these effects were largely driven by female cases. It also highlighted that the timing of stress exposure was important, as earlier exposures (i.e. during childhood) were associated with stronger transcriptional changes. The work described in Chapter 3 provides further cytoarchitectural support that grey matter astrocytes are disproportionately associated with profound early life stress. Astrocytes expressing the glutamate transporter excitatory amino acid transporter 2 were more dense and larger in size in cases that had a history of profound stress during childhood. These modifications were replicated at the bulk level via western blot and inversely correlated with synaptic structure density across the cohort, suggesting that these modifications are associated with changes to the synaptic environment. Finally, the work in Chapter 4 utilised human pluripotent stem cell-derived astrocytes (iAsts) to demonstrate that human astrocytes can be directly impacted by exposure to glucocorticoids. iAsts were highly responsive to the glucocorticoid receptor agonist dexamethasone and demonstrated changes to both neurotransmitter clearance and increases in calcium signalling in response to the neurotransmitters glutamate, N-methyl-D-aspartate (NMDA), and γ-aminobutyric acid (GABA). This provides evidence that core functions of human astrocytes to regulate the synapse can be directly impacted by circulating stress hormones.

This body of work successfully identifies several human-relevant phenotypes in astrocytes related to stress. We identify that human astrocytes can be directly shaped by stress and that prior exposures to stress are also associated with both transcriptional and cytoarchitectural alterations to astrocytes in the human cortex. The evidence from this work indicates that functions of astrocytes in regulating synapses in the grey matter appear to be particularly associated with these stress histories. By focusing on astrocytes, we also highlight that the human brain is persistently impacted by profound stress, particularly during childhood, which has notable implications for treatment and diagnostic specificity.

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Thesis abstract

On the security and robustness of federated learning with application to smart grid infrastructures

Cody Lewis

Abstract of a thesis for a Doctorate of Philosophy submitted to The University of Newcastle, Callaghan, Australia

In the past two decades, machine learning has fast emerged as a popular approach to solving many high-dimensional problems. It focuses on analysing and interpreting patterns and structures in data to enable learning, reasoning, and decision making. A major benefit of machine learning arises from its ability to produce a model or models that can be applied to solve a wide range of problems. For example, machine learning is commonly used in computer vision systems to detect various objects within images, such as traffic signs at a roadside, without having a developer write code that accounts for every possible way that object can be present within an image.

However, machine learning is known to be "data hungry" in that it requires vast datasets with significant amount of variation, to produce accurate models and results. Hence, sourcing of this data can have major implications, especially when it comes to private data pertaining to people. This led to the development of federated learning, which is a form of distributed machine learning across many clients who hold their own independent data that is not shared with the central machine learning model. The clients each train a copy of the machine learning model on their own dataset and upload the resulting trained model to a central server. The server aggregates the client models together to produce a new global model, which is sent back to the clients for the next round of training. The federated learning algorithm aims to maintain data privacy by replacing the requirement that distributed learning needs to have the clients share data, instead tasking them with sharing the model.

Despite its improvements to privacy, federated learning still has several challenges when it comes to security and robustness. In this thesis, we make several theoretical and analytical contributions to the challenges of robustness, privacy and fairness and their combined effects in the federated learning setting.

Robustness is concerned with the ability of the federated learning system to be resilient in the face of attacks or faults. A major class of attacks in federated learning arises due to poisoning, where the clients can intentionally train their model incorrectly (e.g. train a car vision system to recognise stop signs as 40 km/h) and upload the poisoned model to the server to corrupt the global model. We have considered opportunistic adversaries timing their poisoning attacks to undermine robustness mechanisms. We propose the "on-off" attack, where adversaries switch between submitting honest and poisoned updates to fool the stateful variant of robustness mechanisms that are often found in federated learning defence systems (FLDS). We have also proposed good- and bad-mouthing poisoning attacks, where adversaries submit copies (or negated copies) of the target client's update. Such attacks can fool both stateful and stateless robust aggregation systems to either become biased towards the victim or away from the victim. We then propose a robust aggregation algorithm, which helps to mitigate the on-off attack by monitoring the consistency of client updates and punishing those who make sudden and vast changes. Our proposed robust aggregation algorithm simultaneously mitigates the good and bad-mouthing attacks by ensuring that each overly similar update is diminished in influence upon aggregation, to the point that their sum is effectively equivalent to a single update. We analyse our proposed attacks and mitigation strategy, first from a theoretical point of view, and then from an empirical perspective, showing their effectiveness.

The emergence of *gradient inversion attacks* has posed a significant issue to the *privacy* of federated learning. Gradient inversion attacks are often initiated by the server, which observes the updates provided by the clients, and, as a background process, performs a search for the minibatch dataset that produces the same update. If this task is completed successfully, then the server would have violated privacy by recreating the data that the client was not sharing. Recently, gradient inversion attacks have seen many improvements in their effectiveness, for instance, when inverting larger minibatch sizes in the training process and when clients perform a greater number of steps of training. Though some mitigation strategies exist for these attacks, they tend to have significant overheads in terms of network structure, performance trade-offs, and computation time. Moreover, these techniques fail to consider the more recent advancements to gradient inversion attacks. We propose a secure adaptation of the client-side Adam optimisation algorithm to mitigate gradient inversion attacks, with a particular focus on attacks that become more effective as the learning progresses. Our algorithm better mitigates inversion attacks by ensuring that there are always many overlapping samples representative of each class, regardless of the minibatch size, thus confusing recent gradient inversion attacks since they rely on single sample representations for each class. Simultaneously, our algorithm improves the model performance, instead of hindering, unlike many other privacy preserving mechanisms. We prove that this technique prevents inversion attacks and converges effectively, through theoretical and empirical analysis.

Fairness in federated learning tends to have a basis on the equal opportunity to contribute to the global model. We consider the issue of *fairness in the context of device heterogeneity*. Where, to be fair to the clients, the system would have to ensure that it has nearly equal performance with respect to devices with different computational capabilities. Though there have been some prior works addressing this issue, we found that they do not attempt to maximise fairness. For this reason, we propose a federated learning framework that maximises equal opportunity fairness through a game theoretical analysis of the synchronous federated learning setting where clients can train subsets of the global model. We provide theoretical analysis and proofs of our proposed scheme. Additionally, we demonstrate the effectiveness of our proposed scheme using empirical studies. Furthermore, we address the issue of privacy in conjunction with the issue of fairness under device heterogeneity. Solutions to device heterogeneity often require server-side analysis of submitted updates, directly opposing the privacy requirements in federated learning. This motivated us to propose an algorithm that enables secure aggregation while providing fairness with device heterogeneity. This algorithm considers device heterogeneity fairness through model partitioning and then combines this with secure aggregation whereby the clients pad and encrypt their updates to be uploaded. These updates are made to be of the same size as the global model. The server aggregates the gradients forming the sum of gradients that is sent back to the clients. Note that the server is unable to correctly average the parameters under the private setting, as it is not aware of how many clients have updated each parameter. We demonstrate both empirically and theoretically that the proposed scheme has little to no negative impact on performance, and in some cases even improves the performance.

Finally, we apply the techniques that we have developed for robustness, privacy, and fairness to *smart grid infrastructures*. We propose a hierarchical federated learning-based framework for smart grid infrastructure and demonstrate how it improves client dropout and poisoning robustness, using relatively lightweight models suitable for devices with limited computational capability. We provide theoretical justification underlying our design and compare our framework and algorithms empirically with existing relevant works.

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Thesis abstract

Preventing low back-pain recurrence

Natasha Pocovi

Abstract of a thesis for a Doctorate of Philosophy submitted to the Dept. of Health Sciences, Macquarie University, Australia

Low back pain is a common and recurrent condition. To alleviate the burden of low back pain, it is critical to focus on preventing recurrences. Current evidence suggests that exercise with education may help prevent recurrences; however, there is a lack of evidence on the effectiveness of easily accessible and low-cost exercises, such as walking, cycling and swimming. Currently, it is also not possible to accurately predict the likelihood of experiencing a recurrence, which may affect when a patient is offered preventive management. The research contained in this thesis aimed to bridge these gaps.

Chapter Two presents a systematic review of the evidence for walking, running, cycling and swimming to treat and prevent low back pain. The study found these exercises generally provide less benefit than more intensive and targeted alternative interventions (such as physiotherapy and Pilates) but offer more benefit than minimal or no intervention for treating low back pain. The systematic review identified no trials investigating these exercise modes for preventing low back pain. Chapters Three, Four, and Five present the first randomised controlled trial (the WalkBack Trial) of an individualised, progressive walking and education intervention to prevent low back pain recurrences. The trial found that walking and education effectively prevented low back pain recurrences compared to no intervention. The intervention is also highly likely cost-effective and did not increase the overall number of adverse events. Chapter Six presents a qualitative study conducted with a sample of people who participated in the WalkBack intervention to identify motivators for engaging in the prevention-based intervention and identify which elements of the intervention were critical to optimising participant adherence. The study found that the potential prevention of low back pain and anticipated overall health benefits were crucial factors for initially engaging in the intervention. Accountability, diarising activity, and the support of the physiotherapist to coach and progress participants were also important in optimising initial adherence to the intervention. Chapter Seven presents a study that aimed to develop a clinical prediction model to investigate the risk of recurrence in adults who recently recovered from an episode of low back pain. The model's predictive ability was insufficient to recommend its use in clinical practice, highlighting the need for further investigations in this area. In this thesis, an effective, accessible, and low-cost walking and education intervention that significantly reduced recurrences of low back pain has been identified, providing an important advancement in the field of low back pain prevention.

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Thesis abstract

Navigating blue colonialism: the case of large-scale marine protected areas in overseas territories

Constance Rambourg

Abstract of a thesis for a Doctorate of Philosophy submitted to the University of Wollongong, Australia

Overseas territories (OTs) are critical ocean stakeholders, encompassing some of the world's largest exclusive economic zones and marine protected areas (MPAs). Despite their significance in global ocean governance and conservation, there has been minimal study and analysis of the establishment of large-scale marine protected areas (LSMPAs) in OTs, either in academic discourse or in policy debates. This gap is particularly salient given the paucity of studies examining the influence of colonialism in this context, despite it being a pervasive thread running through the past and present of OTs and protected areas alike. The objective of this research is to explore the relationships between colonialism and the implementation and governance of LSMPAs in OTs, along with their equity ramifications. This thesis addresses the gap in study and analysis noted above by asking the following question: To what extent do LSMPAs established in OTs perpetuate colonial power imbalances and inequities? To tackle this overarching question, the study examines: the motivations of metropolitan States in the creation of LSMPAs in their overseas territories; how colonial power dynamics are reflected in the governance structures and decision-making processes of LSMPAs in these territories; and the ways in which the establishment of LSMPAs in OTs may challenge or reinforce the empowerment of these territories and the self-determination of their local and indigenous populations.

The thesis adopts a mixed qualitative methods approach, combining a literature review, an in-depth case study of the Parc Naturel de la Mer de Corail (PNMC) [Natural Park of the Coral Sea], an LSMPA in New Caledonia, and semi-structured interviews with key stakeholders involved in the creation and/or governance of the MPA. Collected data is interpreted using a thematic analysis, identifying patterns, trends, and relationships within the data. The working hypothesis of this thesis, based on reviewed literature, was that LSMPAs in OTs would predominantly reflect colonial power dynamics, reinforcing geopolitical interests of (ex)colonial powers and perpetuating local inequities embedded in the protected areas conservation model. This prompted the introduction of the concept of 'blue colonialism', to describe the persistence of metropolitan States' colonial biases and agendas in marine conservation policies. Case study results revealed a more nuanced understanding of the intersection between marine conservation and colonial legacies in the context of the New Caledonian MPA.

The findings of this thesis demonstrate that while LSMPAs often mirror colo-

nial practices, such as the marginalisation of indigenous voices, they also present OTs and their coastal communities with opportunities to challenge such inequities and advance their local interests and priorities, in and through ocean conservation policies. As international targets like 30×30 gain momentum and LSMPAs expand, this thesis shows that although these tools are influenced by colonial legacies that need addressing to prevent local inequities, they also hold potential for local empowerment and more equitable marine governance.

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Thesis abstract

Application of the REFLUX™ Classifier in the hydrodynamic classification of minerals by particle size

Joshua Starrett

Abstract of a thesis for a Doctorate of Philosophy submitted to
The University of Newcastle, Callaghan, Australia

One of the most important operations in the mineral processing industry is the classification of particles according to their size. These separations are essential for preparing the feed for comminution, or for beneficiation over specific particle size ranges covering density separation or flotation. This study examined the application of the REFLUX™ Classifier in particle size classification, a system consisting of a set of parallel inclined channels above a vertical fluidised bed. A model feed of pure silica was selected and used throughout the study, covering a broad size range up to a nominal 710 µm. A novel feed preparation method ensured the consistent delivery of the feed, not only across a given experiment, but also across the entire study. Mass balance reconciliation became very reliable. This approach of using the same feed proved valuable in linking the different elements of the study.

This work demonstrated the benefit of split fluidisation (side-water) in preventing the entrainment of ultrafine particles to the coarse underflow, whilst not significantly impacting the separation size. The by-pass of ultrafine particles to the underflow was also minimised by ensuring a fluidised bed was present. In the absence of a fluidised bed, the underflow stream would have received a dilute and well mixed flow, resulting in misplacement of fine particles. The overall strategy enabled remarkably sharp separations, with the Imperfection, I, typically as low as 0.11 to 0.13 for solids throughputs up to 92 t/(m² h). The family of partition curves was observed to be very consistent, with strong closure evident at the finer and coarser ends. These results contrast significantly with the relatively poor separations reported in the literature for hydrocyclones and other hydrodynamic separators.

It was found that the lower fluidisation rate acted as the key control variable for separations finer than 200 µm. The required fluidisation velocity was consistent with values calculated using the Richardson and Zaki (1954) equation. However, at coarser separation sizes, the side-water became much more important, especially for the more concentrated feeds. In order to minimise the water consumption, the REFLUX™ Classifier was modified by halving the lower cross-sectional area of the vessel. This modification delivered a doubling of the superficial fluid velocity for a given flow rate, and helped to address the increasing challenge of producing sharp separations at these coarser sizes.

To ensure sharp separations, it was also demonstrated that the volumetric water-to-solids ratio in the overflow needed to be at least 5.5. Below this point, the high internal solids concentration within the inclined

channels likely impeded the ability of the coarser particles to segregate, misplacing them into the fine overflow. By providing sufficient water through either the feed or the side-water, coarse particles were efficiently rejected by the inclined channels and correctly reported to the coarse underflow. Whilst most of this work was completed at solids concentrations of 50 wt.% in the feed, solids concentrations as low as 2–8 wt.% were also examined. In these cases, high volumetric feed fluxes produced Imperfections as low as 0.06, less than half that of the other experiments in this study, further demonstrating the positive effect of lower solids concentrations in the inclined channels.

The maximum solids throughput was shown to be proportional to the separation size. Moreover, the separation size correlated directly with the underflow solids yield. At lower separation sizes, and therefore higher underflow yields, the higher downwards flux led to a higher solids concentration above the fluidised bed. When this solids concentration increases to the point of converging with that of the fluidised bed, the height of the bed is no longer discernible, meaning the system becomes flooded. Therefore, finer separations required lower solids throughputs, whilst coarser separations could accommodate much higher solids throughputs.

Through all the experiments in this study, it was discovered that the inferred internal concentration correlated directly with the suspension viscosity, and in turn linearly with the Imperfection. This internal concentration was based on the well-established empirical model of Laskovski et al. (2006). An empirical model was then developed to describe the separation performance of the REFLUX™ Classifier based on a given separation size, and information of the total solid and water inputs. Using an assumed underflow solids concentration, often ~65 wt.% in this work, the water and solid outputs were calculated for each stream, and the overall Imperfection determined. This empirical model therefore provides a complete description of the REFLUX™ Classifier in separating silica based on particle size across the full range of conditions in this study.

The strength of the data in this study allowed for direct comparisons to be made between two of the most common distributions used in the field of size classification — the Whiten equation, and the Rosin-Rammler function. The experimental data from this work adhered to the Whiten equation over a range of $\pm 5E_p$, much wider than that of the Rosin-Rammler function, providing significant evidence in favour of the Whiten equation. It was also discovered that the Whiten equation has a functional equivalence to the fundamental Fermi-Dirac distribution used in quantum mechanics, which is governed by a Boltzmann distribution incorporating a chemical potential difference. This equivalence offers prospects for an improved framework for describing the role of a hydrodynamic driving force in particle size classification.

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Thesis abstract

Olagija Research: A collaborative journey in relational truth-telling

Lillian Tait

Abstract of a thesis for a Doctorate of Philosophy submitted to Macquarie University, Australia

Wen yu lugumbat stori yu garra gu ebri lil bush trek weya ola stori im be.

When you're searching for stories you've got to go along every little bush track to where all the stories are located (Rhonda, 14 May 2019).[1]

This thesis stories a collaborative truth-telling journey led by Ngalakgan Country and Ritharrŋu sisters Margaret and Rhonda Duncan with settler doctoral student Lillian Tait. Our research journey has taken us from Urapunga community on Ngalakgan Country in the Roper Region of the Northern Territory across the Top End of Australia, along 'bush tracks' and highways, into board rooms, living rooms, and deep within the colonial archive. It has been led by Margaret and Rhonda's questions surrounding their father's mysterious origins. While captivating, many of the stories encountered along our journey do not feature in this thesis, rather they have been written into a bi-lingual book titled *Lugubatbat Stori: Our search for the truth about our dad* (Duncan and Duncan, forthcoming), written primarily for younger generations of family. This thesis, on the other hand, documents our approach to doing collaborative and anticolonial research guided by ethics of relationality, reciprocity and care.

The thesis documents our approach to looking for stories by engaging with Country, storytellers and archives; telling stories through art that centres Ngalakgan Country, sovereignty and survivance; and, telling stories through words via co-analysis, co-writing and co-translation. This work is one part of a larger journey of reciprocity, which builds on existing relationships between co-researchers and extends Masters-level research. Such process unsettles academic norms of doctoral research as a discreet and isolated journey.

Our research contributes to growing calls for greater truth-telling about Australia's past and present. It offers a community- and Country-led methodology involving co-creative multisensory methods for engaging with place, people and stories across, through and as time. Truths are understood here as stories in and of the land — they are plural, unfinished and always in emergence. I argue truth-telling needs to go beyond telling to doing through an ethical agenda that is:

- relational: centring relationships between people and/as Country in decision making and research practice;
- responsive: attending to the situated and diverse needs of people, place and time, which is by nature, subject to change; and,

1 Dr. Tait has asked that we note the names of her collaborators Margaret and Rhonda Duncan.

- recuperative: intentionally wrapping painful stories with love in order to weave generative stories that connect people with their responsibilities to and as part of place and time.

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Thesis abstract

Efficient perovskite single junction and perovskite silicon double junction solar cells

Guoliang Wang

Abstract of a thesis for a Doctorate of Philosophy submitted to the School of Physics, The University of Sydney, Australia

Photovoltaic device has already played a significant role towards a net-zero future as it accounts for around three-quarters of renewable capacity additions worldwide in 2022. Next generation perovskite solar cells (PSCs) with their high efficiency credentials may further contribute to lowering the cost of power generation especially when implemented in a tandem cell configuration. To improve their commercial viability, the first part of the thesis studied perovskite crystallization process in ambient air. New insights were developed and was utilised to develop a thermal-radiation-assisted cyclization process to minimize the detrimental effect of moisture in perovskite crystallization in air. As a result, comparable power conversion efficiency were obtained compared to devices fabricated in inert atmosphere. For high efficiency perovskite-silicon tandem devices, a new self-assembly monolayer hole selective transport layer was designed, synthesised and applied in wide bandgap (1.67eV) perovskite and perovskite-silicon tandem. As a result, 28.9% PCE was achieved. Additionally, the encapsulated tandem cell passed the International Electrotechnical Commission (IEC) 61215 Thermal Cycling (200 cycles between –40 °C and 85 °C) test. The third part of the thesis reported an innovative use of morpholinium bromide (MLBr) as an interlayer between perovskite and C60 in wide bandgap perovskite and perovskite-Si solar cells. The choice of the more cost effective MLBr was innovative retaining the chemical structure and therefore benefit of piperidium bromide (PpBr) while the additional oxygen atom induces an electron rich environment for a larger dipole moment to enable better charge extraction to the C60. The impact of this work was demonstrated by the stability of the encapsulated MLBr and PpBr devices, which retained 97% of their initial efficiency after 400 thermal cycles, twice the number of cycles specified by the IEC 61215 photovoltaic module standard.

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Thesis abstract

Data-efficient and generalizable machine learning in complex environments

Xiaobo Xia

Abstract of a thesis for a Doctorate of Philosophy submitted to the Faculty of Engineering, The University of Sydney, Australia

In an age marked by an unprecedented influx of data across diverse domains, the quest for effective machine learning (ML) solutions has increased significantly. However, data imperfections in complex environments present formidable obstacles, encompassing defective, redundant, and scarce data. Specifically, defective data, characterized by annotation errors and incompleteness, obstruct the learning process, particularly in critical domains such as healthcare and finance. Redundant data overwhelm relevant insights, demanding efficient filtering techniques for optimal ML performance. Besides, scarce data that are prevalent in domains with limited examples, necessitate robust ML models capable of generalizing effectively. Addressing these challenges is pivotal for unlocking the full potential of ML technologies. This thesis offers innovative solutions across three key areas: learning with defective data, redundant data, and scarce data. Particularly, for defective data, it explores learning with mislabelled and incomplete data, which proposes novel methods for handling each scenario. In the realm of redundant data, the thesis introduces a moderate coreset selection technique to enhance ML efficiency across diverse practical tasks, and a refined coreset selection strategy to reduce the size of the constructed coreset while maintaining satisfactory model performance. Additionally, it addresses the challenge of scarce data by proposing advanced strategies for kernel mean estimation and augmenting datasets by marginalized corruption distributions to improve sample efficiency and model generalization. This thesis provides comprehensive insights and solutions for learning with imperfect data. By addressing these obstacles, it promotes the development of data-efficient and generalizable ML, and lays the groundwork for transformative breakthroughs in fields such as healthcare, finance, and climate science, propelling innovation and progress fuelled by the power of ML.

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Thomas Julius Borody (1950–2025) FRSN

Emeritus Professor Robert Clancy AM FRSN

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Thomas Julius Borody died on 4 October 2025 from the complications of a chronic illness. Born on 12 January 1950, he was 75 years old. Tom was probably the last of the great Australian individual physician-scientists working from a solo medical practice, supporting his research through his clinic. History will record his ground-breaking research, always focussed on what most affected his patients — the big questions — and always coming up with the big answers. He was a proud Fellow of the Royal Society of NSW, reflecting the spirit of those founding forefathers of NSW science.

Tom came to Australia from Poland, never losing that connection through a loyal Polish patient cadre. A stellar academic career, beginning at the University of NSW, then St Vincents Hospital, the Garvin Institute, and the Mayo Clinic was followed by his establishing the Centre for Digestive Diseases (CDD) in Five Dock, Sydney, in 1984. Prior to commencing at the CDD, he spent time as a medical missionary in the Solomon Islands, an experience he credited with influencing his approach to solving clinical problems, with a particular focus on manipulating pathology caused by microbes. Tom would become recognised internationally as a world-leading clinical scientist for his extraordinary contributions to managing dysbiotic microbiomes (that is, disease caused by distortion of the normal bacterial populations residing in the gut through the appearance of bacteria linked to a disease). Regularly, at international medical meetings, I would be asked "where is Tom Borody?" before any other Australian medical scientist. The reason is that he made a difference in the gastroenterological challenges of the day.

Few are aware of the extent that his discoveries changed the lives of millions throughout the world.

First, peptic ulcer disease. For those of us working as hospital residents in the 1960s through to the mid-1980s, no matter whether you were on a medical or surgical team, your days and nights were dominated by complications of peptic ulcers in the stomach and duodenum — life-threatening haemorrhage, perforated ulcers, stenotic obstruction, penetrating ulcers or ulcer-related carcinoma of the stomach were part of your daily activities, as 20% of men would develop an ulcer. Ulceration involving the stomach and duodenum was the medical tsunami of the 20th century. Our colleagues Barry Marshall and Robin Warren deservedly received the Nobel Prize in Physiology and Medicine in 2005 for recognising the association of *Helicobacteria pylori* with duodenal and gastric ulcers at a time when we all believed in the "Wilfred Card" paradigm that ulcers were due to the outcome of "acid + pepsin vs mucosal resistance." To neutralise the acid, we filled patients with calcium carbonate to the point of toxicity. The problem was that Marshall and Warren were unable to eradicate the bacteria and thus unable to prove causation. Borody drew on his experience with tuberculosis in the Solomon Islands. This taught him the importance of combination antibiotic regimens. Marshall had shown that a combination of bismuth and certain antibiotics could reverse gastritis and give relief, but the condition often recurred. Borody discovered that combining bismuth, metronidazole and tetracycline cured 96% of duodenal ulcers and eradicated *H. pylori* in over nearly all cases. By showing that eradication of *H. pylori* and duodenal ulcers persisted with ulcer recurrence at less than 1% per year, Borody had established causation. He further refined treatment to include a proton pump inhibitor to suppress acid secretion and then developed his "escape" therapy to eradicate resistant *H. pylori* resulting from abbreviated commercial therapies.[1] A review of the impact of Borody's discovery of Triple Therapy 25 years after its introduction in Australia in 1985 estimated a saving of 18,000 lives, 260,000 life years, 33,000 productive life years and in excess of $10 billion![2]

Borody's second discovery rivals his triple therapy in importance. It would transform interest and occasional forays into faecal transplantation into clinical relevance. It began with a study published as a letter in the *Australian Medical Journal* in 1989, showing benefit following faecal microbiome transplantation (FMT) in a group of recipients with *Clostridium difficile* (a life-threatening infection), inflammatory bowel disease and irritable bowel disease.[3] FMT cures *C. difficile* in over 90% of cases. Over the subsequent 25 years, 14,000 FMTs have been performed at the CDD, with Borody recognised as the modern "father" of microbiome replacement therapy. New therapeutic targets included systemic disorders such as Parkinson's disease and autism. It was Borody's keen observation of collateral benefits in these patients, treated for a primary gut problem, that opened up FMT to wider fields.

The third discovery was to expand on earlier limited studies in Crohn's disease to develop a triple antibiotic therapy focussed on intracellular bacteria. Successful clinical trials aimed at reducing the load of *Mycobacterium avium s. Paratuberculosis* (MAP) in Crohn's patients provides a major new approach to managing a disease of growing importance. Current therapy aims only at suppressing the inflammatory response to persistent intracellular bacteria, therapy that is symptomatic but fails to eradicate the primary cause. Combining triple anti-MAP antibiotic therapy with FMT in a group of patients with Crohn's gave complete remission without therapy for many years, leading Borody to claim a "cure" for this major blight on humanity.

To these three major contributions, others can be added. They include improved bowel preparations for colonoscopy, anaesthetic apparatus improvements, drug treatment combinations for constipation, parasitic disease — the list goes on. His last significant contribution was in COVID. The early phase of the pandemic was consumed

1 See Borody TJ (2021) *Helicobacter pylori* causes peptic ulcers. *JProcRSNSW* 154: 44–46. https://doi.org/10.5962/p.361954

2 Eslick GD et al. (2020) Clinical and economic impact of "triple therapy" for *Helicobacter pylori* eradication on peptic ulcer disease in Australia. *Helicobacter* 2020;00: e12751. https://doi.org/10.1111/hel.12751

3 Borody TJ et al (1989) Bowel-flora alteration: a potential cure for inflammatory bowel disease and irritable bowel syndrome. *Medical Journal of Australia*, 150, May: 604. https://doi.org/10.5694/j.1326-5377.1989.tb101176.x

in misinformation, with available repurposed drugs avoided as a threat to newly developed genetic vaccines. Tom developed an effective "triple drug therapy" based on ivermectin, doxycycline and zinc which remains in development. As with other ventures attracting controversy at the time, he is supported by science and history, with ivermectin confirmed as safe, effective and cheap in 53 randomised controlled trials.

Few have achieved the success reached by Tom Borody in one major area of medicine, let alone three. He built a clinical research unit within a full-time private clinic, without the advantages enjoyed by career academic medical scientists. His award by thesis of a DSc is most unusual, if not unique, amongst full-time clinicians in private practice. In 2004, *The Australian Medical Journal* celebrated 90 years of publication by listing the ten most cited papers over that time: two were by Nobel Prize winners Warren and Marshall; another two were by Tom Borody.

My association with him came from a search for a gastroenterologist prepared to work with an academic by allowing development of a wet laboratory in his clinic to gather and process specimens — Tom's hand was the only one raised. An incredibly productive collaboration followed (and continued until COVID-19) with new insights into immune dysfunction in *H. pylori* disease and Crohn's disease and the first trial of a "yes/no" test for *H. pylori* using finger-prick blood (the precursor for RAT tests used in COVID diagnosis). This experience reflected the intellectual enquiry and generosity of spirit Tom Borody had in sharing his time and resources to find answers to important questions. He was a warm, generous and kind person — fun to be with but always challenging!

This obituary reflects a personal experience with a great man — we shared science, clinical work, and a close personal relationship for more than 25 years. The long list of medical contributions does not capture the extraordinary commitment and quality relationship Tom Borody had with every patient: from film stars flying in from the US for the day, to a local pensioner living across the road, every patient was equally important. Every patient was a friend, often sharing mobile phone numbers. They saw in him a capacity to individualise their medical problem, to think outside the square and to treat them and their medical problem as unique. His boundless enthusiasm exhausted all but him — exchanging emails at midnight several times a week, always finished with Tom sending the last contribution to whatever the challenging question of the day may be.

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Benno Paul Schoenborn (1936–2025)

Rob Knott MRSN

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The scientific community mourns the passing of Benno Schoenborn, a distinguished scientist with an outstanding career in structural biology. He died on 23 September 2025 in Phoenix, Arizona. Benno was born on 2 May 1936 in Basel, Switzerland, and grew up in Berne, but, as an indication of the man-before-his-time, rather than continuing a traditional Swiss education, he regarded the world as his classroom.

After receiving his BA in Physics from the University of California Los Angeles in 1958, a chance meeting inspired him to redirect his studies to biomolecular structure. Of all the opportunities available to him, he chose the Physics Department at the University of NSW to study for his PhD, awarded in 1962. During this time, Benno formed many scientific collaborations and friendships, and especially a lifetime friendship with Jak Kelly, a past President of the RSNSW. Benno was a member of the Society for many years.

After his PhD studies, Benno returned to the US to continue his career at the Brookhaven and Los Alamos National Laboratories. The list of achievements during his career is extraordinary. Benno is rightly the "father" of neutron protein crystallography, a technique which leads to a greater understanding of biomolecular structure and function by locating hydrogen in exquisite detail. He received the Ernest Orlando Lawrence Award in 1980, a DSc (hon.) from the New Jersey Institute of Technology in 1982, and the American Crystallographic Association Bau Neutron Diffraction Award in 2016 for his pioneering work on neutron crystallography and its application to biology. There were also many achievements in other X-ray and neutron-scattering techniques, complex computation and sophisticated instrumentation. He was an adjunct professor at Columbia University and taught at numerous universities in the US, the UK, Europe, and Australia.

Benno returned to Australia many times for work (at UNSW, University of Sydney, and ANSTO), for family, and to enjoy our more relaxed lifestyle. Benno's scientific insight was extraordinary and his remarkable sense of curiosity drove many innovations. He was an inspiration and mentor to many.

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Royal Society of New South Wales 2025

Awards Winners 2025

The Awards for 2025 were announced at the 1337th Ordinary General Meeting of the Society, held on Wednesday, 3 December 2025.

Four Career Excellence Awards

2025 RSNSW James Cook Medal

Professor Michelle Haber AM FAA FAHMS (Children's Cancer Institute and UNSW)

2025 RSNSW Edgeworth David Medal

Scientia Professor Xiaojing Hao FTSE FAA (UNSW)

2025 RSNSW Ida Browne Early Career Medal

(No applicants in 2025.)

2025 RSNSW Aboriginal and/or Torres Strait Islander Scholars Medal

Professor Bradley Moggridge FTSE (UTS)

Four Discipline Awards

2025 RSNSW Liversidge Award and Lectureship in the Chemical Sciences

Professor Chuan Zhao (UNSW)

2025 RSNSW Award in the Life Sciences

Professor Richard Kingsford AO FRSN FRZS (UNSW)

2025 RSNSW Warren Award in Engineering, Technology, Architecture and Design

Professor Simon Ringer (University of Sydney)

2025 RSNSW Award in the Creative and Performing Arts

Scientia Professor Dennis Del Favero FAHA (UNSW)

Three 2025 RSNSW Bicentennial Early Career Research Citations

Dr Jiayan Liao (UTS), *Dr Brandon Munn* (University of Sydney), *Dr Adrian Y. S. Lee* (Westmead Institute of Medical Research, University of Sydney)

Four 2025 RSNSW Bicentennial Postgraduate Scholarships

Isabelle Nicolas (Macquarie University), *Eilish McMaster* (Sydney University), *Christopher Whyte* (University of Sydney), *Amir Tourani* (Western Sydney University)

Four Career Excellence Awards

2025 RSNSW James Cook Medal

The James Cook Medal is awarded for the most meritorious lifetime contributions to knowledge and society in Australia or its territories made by an individual and conducted mainly in NSW. The James Cook Medal was established by the Council in 1943 following a donation made by Henry Ferdinand Halloran to celebrate his 50 years as a member of the Society and it has been awarded periodically since 1947. In 2023, the Council determined to award it annually.

Professor Michelle Haber AM FAA FAHMS (Children's Cancer Institute and UNSW)

Few individuals have had such a sustained, transformative impact on science, medicine and community outcomes — and fewer still have an equal record of advancing knowledge, building institutions, and translating discoveries into lifesaving practice — as Professor Michelle Haber. Across more than four decades, she has shaped the field of childhood cancer research both nationally and internationally. She has contributed seminal discoveries in cancer biology, pioneered new diagnostics and therapies, and created enduring national frameworks that ensure children with cancer in Australia now benefit from world-leading personalised medicine programs.

2025 RSNSW Edgeworth David Medal

The Edgeworth David Medal is awarded for the most meritorious contributions to knowledge and society in Australia or its territories, conducted mainly in NSW by an individual who is from 5–15 years post-PhD or equivalent on 1 January of the year of the award. The Edgeworth David Medal was established by Council in 1943 in honour of Sir T. W. Edgeworth David FRS, who compiled the first comprehensive record of the geology of Australia, and following a donation made by Henry Ferdinand Halloran to celebrate his 50 years as a member of the Society. It has been periodically awarded since 1948. In 2023, the Council determined to award it annually.

Scientia Professor Xiaojing Hao FTSE FAA (UNSW)

Professor Xiaojing Hao is at the international forefront of developing cost-effective thin-film semiconductor materials to harvest sunlight for future photovoltaic technology, products and applications. She has made vital contributions to photovoltaic science and engineering by providing unique solutions for improved performance of several types of emerging thin-film photovoltaic devices, and developing efficient, cheap and environmentally friendly thin-film materials. Her work represents a significant and lasting contribution to the advancement of knowledge in this field, strengthening Australia's international standing in photovoltaics and marking her as a scientist of distinction.

2025 RSNSW Ida Browne Early Career Medal

The Ida Browne Early Career Award recognises the most meritorious contributions to knowledge and society in Australia or its territories by an individual from 0–5 years post-PhD or equivalent on 1 January of the year of the award and conducted mainly in NSW. The Ida Browne Medal was established by the Council in 2023 in honour of Ida Browne DSc, a palaeontologist and the first woman President of the Royal Society of NSW, who served from 1953–1954.
(No applicants in 2025.)

2025 RSNSW Aboriginal and/or Torres Strait Islander Scholars Medal

The Aboriginal and/or Torres Strait Islander Scholars Medal is awarded for the most meritorious contributions to knowledge and society made by scholars identifying as Australian Aboriginal or Torres Strait Islander and conducted mainly in NSW. The Aboriginal and/or Torres Strait Islander Scholars Medal was established by the Council in 2023 to reflect the full scope of the Society's values.
Professor Bradley Moggridge FTSE (UTS)

Professor Bradley Moggridge is a Kamilaroi man and the Associate Dean (Indigenous Leadership and Engagement) in the UTS Faculty of Science. He is a global leader in water research and climate change, focused on the integration of Traditional Aboriginal knowledge and Western science to provide a holistic approach to the management and repair of Country. Professor Moggridge's 25 years' experience spans water and environmental science, cultural science, regulation, Indigenous engagement, water policy and hydrogeology. His strong research publication record informs his extensive and highly sought-after engagement advising on high-profile expert panels, with professional societies, on advisory groups, RAP committees and boards.

Four Discipline Awards

2025 RSNSW Liversidge Award and Lectureship in the Chemical Sciences

Awarded for distinguished research in any area of the Chemical Sciences, conducted mainly in New South Wales. Recipients may be resident in Australia or elsewhere. The Liversidge Lectureship was established in 1931 by the Royal Society of NSW in conjunction with the Royal Australian Chemical Institute (RACI), in honour of Archibald Liversidge MA LLD FRS, Professor of Chemistry at The University of Sydney and one of the Society's Council members who sponsored its Act of Incorporation in 1881. In 2023, Council designated it the Royal Society of NSW Liversidge Award and Lectureship.
Prof Chuan Zhao (UNSW)

Prof Chuan Zhao has become the leading electrochemist in Australia. His recent award of a $3M ARC Laureate Fellowship testifies to his standing in Australian science. His field of research, the production of green chemicals and sources of energy by electrochemistry, is actively contributing to the nation's fight against climate change. He has been the world record holder for the efficiency of hydrogen production by electrolysis of water. Prof Zhao's work has been recognised by numerous awards and fellowships, including FRSN, FRACI, FRSC, FTSE, FIAAM, the HG Smith Memorial Award (2024) and RH Stokes Medal (2023) of the RACI.

2025 RSNSW Award in the Life Sciences

Awarded for distinguished research in any area of the Life Sciences, excluding veterinary and medical sciences, conducted mainly in New South Wales. Recipients may be resident in Australia or elsewhere. Council established the Royal Society of NSW Life Sciences Award in 2023 to reflect the full scope of the Society's founding values.

Professor Richard Kingsford AO FRSN FRZS (UNSW)

Professor Richard Kingsford is widely regarded as one of Australia's most prominent and respected experts on waterbird, wetland and river ecology, with the majority of his 30+ year career having been focused on restoring and protecting the wetland ecosystems of NSW. Over the past decade he has extended his influence to terrestrial ecology, leading the Wild Deserts Partnership Project in far western NSW, reintroducing locally extinct mammal species and controlling feral predators. His long-term contribution to environmental science in NSW has been nothing short of transformational.

2025 RSNSW Warren Award in Engineering, Technology, Architecture and Design

Awarded for distinguished research in any area of Engineering, Technology, Architecture and Design, conducted mainly in New South Wales. Recipients may be resident in Australia or elsewhere. The Warren Award honours William Henry Warren, Foundation Professor of Engineering at The University of Sydney, establishing the first faculty of engineering in New South Wales in 1884. He was founding President of the Institution of Engineers, Australia, and twice President of the royal Society of NSW.

Professor Simon Ringer (University of Sydney)

Professor Simon Ringer is a globally recognised materials engineer whose research has redefined how solute atoms govern microstructure and properties in metals and semiconductors. His breakthroughs have resolved long-standing property conflicts and translated into industrial technologies in steel, aluminium, and advanced alloys worldwide. His innovations in electron microscopy and atom probe tomography have delivered unprecedented atomic-scale insights, advancing both fundamental science and applied engineering. His leadership has transformed NSW's research landscape through both new centres and institutes, and establishing new national research facilities, expanding our capacity to make, measure and model for knowledge creation, industrial impact, and Australia's technological competitiveness.

2025 RSNSW Award in the Creative and Performing Arts

Awarded for distinguished research in any area of the Creative Arts and/or Performance, conducted mainly in New South Wales. Recipients may be resident in Australia or elsewhere. Council established the Royal Society of NSW Creative and Performing Arts Award in 2023 to reflect the full scope of the Society's founding values.

Scientia Professor Dennis Del Favero FAHA (UNSW)

Scientia Professor Dennis Del Favero FAHA is a distinguished scholar in the field of Visual Arts, whose research has resulted in frontier advances in intelligent visualisation systems. His research has involved developing and integrating artistic, conceptual, and technological advances in contemporary art using immersive aesthetics and AI. These have been developed through basic research projects with outcomes translated into applied research for field-leading industrial applications for major museums, media, performing arts, mining and emergency organisations. His work has been nationally and internationally praised for its exceptional artistic quality, as well cultural and social utility.

Three 2025 RSNSW Bicentennial Early Career Research Citations

The RSNSW Bicentennial Early Career Research and Service Citations are awarded each year to recognise outstanding contributions to research and service to the academic and wider community. Applicants must, on 1 January of the year of nomination, be no more than 5 years after the award of their PhD or equivalent by a university or other research institution in NSW or the ACT.

For 2025, three RSNSW Early Career Citations have been awarded:

- Dr **Jiayan Liao** (UTS)
- Dr **Brandon Munn** (University of Sydney)
- Dr **Adrian Y. S. Lee** (Westmead Institute of Medical Research, University of Sydney)

Dr Jiayan Liao is an award-winning nanophotonics researcher and NHMRC EL1 Fellow whose work is transforming molecular diagnostics. With 90+ publications, over $2M in funding, and industry-translated discoveries, she also contributes actively to the academic and broader community. She mentors over 10 HDR students and ECRs, serves on editorial boards, and promotes diversity in STEM through outreach and public engagement. International collaborations and industry partnerships are advancing her research in imaging, cancer diagnostics, and pandemic preparedness. Recipient of the NSW Premier's Prize (2024) and the NHMRC Research Excellence Award (2023), she exemplifies excellence, service, and leadership in science.

In a groundbreaking study recently published in Cell, **Dr Munn** and others uncovered a universal principle of brain organisation that unifies competing theories of neural coding. We found brain activity follows a multiscale hierarchy that is conserved across five phylogenetically diverse species from zebrafish to nonhuman primates. This structure allows the brain to balance efficiency and resilience and flexibly reconfigure during behaviour. Using physics-inspired analyses and network modelling, we show that this organisation enhances information flow. By revealing a fundamental law of brain function, this discovery provides a powerful new foundation for understanding cognition, neurological disease, and the design of future artificial-intelligence technologies.

Dr Lee is a clinician-scientist specialising in autoimmunity and Sjögren's disease (SjD). As an emerging leader in the field (SciVal FWCI 1.53), he established the first SjD biobank and registry in New South Wales and is completing his PhD in this area. Lee is a strong advocate for SjD patients, engaging with them internationally and working with patient-driven organisations. He has published over 100 peer-reviewed papers, mentored young researchers, and spoken at conferences. Through his work, Lee aims to understand SjD's immunological mechanisms and promote research to improve patient outcomes. His dedication has significantly advanced SjD research and awareness.

Four 2025 RSNSW Bicentennial Postgraduate Scholarships

The RSNSW Bicentennial Postgraduate Scholarships are awarded each year to recognise outstanding achievements by young researchers in any academic field. Applicants must have completed an undergraduate degree within NSW or the ACT and must on 1 January of the year of nomination be enrolled as research students in the first or second year of their first higher degree at a university or other research institution in NSW or the ACT.

For 2025, four RSNSW Scholarships have been awarded:

- **Isabelle Nicolas** — BA (Sydney), JD (Sydney), MRes (Macq), currently a PhD candidate at Macquarie University
- **Eilish McMaster** — BAdvSci (UQ), currently a PhD candidate at the University of Sydney
- **Christopher Whyte** — BSc (Macq), MPhil (Sydney), MPhil (Cantab), currently a PhD candidate at the University of Sydney
- **Amir Tourani** — BSc (Sari Agricultural Sciences and Natural Resources University, Iran), MSc (Shahed University, Iran), currently a PhD candidate at Western Sydney University

Isabelle received the award based on the letters from nominators attesting to her contributions and capability, and her publication: Nicolas I (2024) Striking the balance: anti-money laundering goals and legal privilege in Australia. *Current Issues in Criminal Justice* 37(2): 208–227. https://doi.org/10.1080/10345329.2024.2420146

Eilish received the award based on the letters from nomimators attesting to her contributions and capability, and her publication: McMaster ES, Dimon RJ, Baker AG, Harre C, Mallee J, Maric A, Richards P, Wiseman M, Ho SYW & Rossetto M (2025) Combining spatial, genetic, and environmental risk data to define and prioritize in situ conservation units. *Ecology and Evolution* 15(5): e71251.

Christopher received the award based on the letters from nomimators attesting to his contributions and capability, and his publication: Whyte CJ, Müller EJ, Aru J, Larkum M, John Y, Munn BR & Shine JM (2025) A burst-dependent thalamocortical substrate for perceptual awareness. *PLOS Computational Biology* 21(4): e1012951. Link: https://journals.plos.org/ploscompbiol/article?id=10.1371/journal.pcbi

Amir received the award based on the letters from nominators attesting to her contributions and capability, and her publication: Tourani AH, Katlav A, Cook JM & Riegler M (2024) Mating receptivity mediated by endosymbiont interactions in a haplodiploid thrips species. *Proceedings of the Royal Society B* 2024 Oct 30; 291:20241564. https://doi.org/10.1098/rspb.2024.1564

Events in 2025

Meetings were held by the Society in five places: Sydney; Newcastle by the Hunter Branch; Mittagong by the Southern Highlands Branch; western NSW by the Western NSW Branch; Armidale by the New England North West Branch.

1329th OGM and Open Lecture

Distinguished Professor Ian Paulsen FRSN FAA FASM, Director, ARC Centre of Excellence in Synthetic Biology Macquarie University, "Inspired by Nature, Designed by Science," 5 February, Metcalfe Theatre, State Library of NSW

Annual Meeting of the Four Societies 2025 (Australian Institute of Energy, Engineers Australia, Royal Society of NSW, Australian Nuclear Association)

Dr Robert Barr AM FIEAust CPEng, Director Electric Power Consulting, "Integrating nuclear generation into the Australian electricity grid," 19 February, Engineers Australia Sydney Offices, 44 Market Street, Sydney

Southern Highlands Branch Meeting 2025-1

Susannah Fullerton OAM FRSN, Author, Literary Lecturer, and Tour Leader, "Dr Johnson's Dictionary," 20 February, RSL Mittagong, Carrington Room

Ideas@theHouse: February 2025

Dr Sarah Britton, Director, One Health Unit Interim Australian Centre for Disease Control Department of Health and Aged Care, "Where Worlds Collide: Exploring the wild/domestic animal-human interface in One Health," 20 February, Government House, Sydney, https://youtu.be/6GYERoCLadk

RSNSW Student Award and Early Career Citation Presentations

Mr David Sweeney, University of Sydney; Mr Muyang Li, University of Sydney; Mr Joel Sved, University of Sydney; Ms Linqing Tian, UNSW Sydney; Dr Fei Deng, UNSW Sydney; Dr Jennifer Matthews, University of Technology Sydney; Dr Cynthia Turnbull, Australian National University, 5 March, University of Technology Sydney, UTS Central (Building 2) Foyer, Ultimo

RSNSW 2025 Annual Dinner and Presentation of Awards

Professor Georgina Long AO FAHMS FAA, 2024 Australian of the Year, recognised for her ground-breaking research on targeted therapies for melanoma., 7 March, Strangers' Room, Parliament House, Sydney,

Southern Highlands Branch Meeting 2025-2

Dr Craig Barker, Head, Public Engagement Chau Chak Wing Museum University of Sydney, "The Curator and the Cats: The Curious Story of Professor James Stewart and the Archaeology of Ancient Cyprus in Australia," 20 March, RSL Mittagong, Carrington Room

Hunter Branch Meeting 2025-1

Dr Hannah Schunker, ARC Future Fellow School of Information and Physical Sciences, University of Newcastle, "Our Magnetic Sun," 20 March, NEX, Newcastle Exhibition and Convention Centre, 309 King Street, Newcastle West, https://youtu.be/8StOJlxxh-M

Frontiers of Science Forum 2025

Associate Professor Benjamin Pope, Macquarie University; Emeritus Professor Liz Harry, University of Technology Sydney; Associate Professor Helen Georgiou, University of Wollongong; Dr Vipul Agarwal, UNSW Sydney, "Exploring major discoveries and theories in physics, mathematics, biology, and chemistry," (A joint presentation of the Australian Institute of Physics, the Teachers' Guild of NSW, the Royal Australian Chemical Institute, and the Royal Society of NSW.), 28 March, Concord Golf Club, 190 Majors Bay Road, Concord

1330th OGM and Open Lecture

Professor Hugh Durrant-Whyte FRS FREng FAA FIEEE HonFIEAust, NSW Chief Scientist and Engineer, "Engineering the Future," 2 April, Michael Crouch Room, Mitchell Building, State Library of NSW, https://youtu.be/unJX_esfweI

Lunchtime series: Provocations and Inspirations (April 2025)

Professor Chris Turney FRSN FRSA FRMetS, Pro Vice-Chancellor (Research) University of Technology Sydney, "Extreme Earth: Antarctica's climate warning for the future and what we can all do about it," 15 April, Union University and Schools Club, 25 Bent Street, https://youtu.be/B9T1uOam-zs

Western NSW Branch Meeting 2025-1

Distinguished Professor Chris Blanchard, Professor of Food Science, Gulbali Institute, Charles Sturt University, "Is my food killing me?" 16 April, Live streaming, https://youtu.be/ryP_wHzdcGY

Southern Highlands Branch Meeting 2025-3

Associate Professor Mark Cowley, Deputy Director, Enabling Platforms and Collaboration Children's Cancer Institute, "Using Precision Medicine to Eradicate Childhood Cancer," 17 April, RSL Mittagong, Carrington Room

1331st OGM and Open Lecture

Scientia Professor Jane McAdam AO FASSA FAAL, Kaldor Centre for International Refugee Law, Faculty of Law & Justice, UNSW Sydney, "Rethinking Mobility in a Changing Climate," 7 May, Live streaming, https://youtu.be/oyBMbtQdBHM

Hunter Branch Meeting 2025-2

Professor Thomas Nann, Founder and Chief Executive Officer, Allegro Energy, Newcastle, "From Test Tubes to Terawatts: How Research Sparked a Battery Business," 15 May, NEX, Newcastle Exhibition and Convention Centre, 309 King Street, Newcastle West, https://youtu.be/s3MGBNzXO-M

Southern Highlands Branch Meeting: 2025-4

Professor Geraint Lewis FRSN FLSW Sydney Institute of Astronomy, School of Physics, University of Sydney, "Rare or Everywhere — Life in a Hostile Universe," 15 May, RSL Mittagong, Carrington Room

RSNSW Visits Program 2025-1

The University of Sydney: Chau Chak Wing Museum and Fisher Library, 2 June , The Chau Chak Wing Museum, University Place, and Fisher Library, Eastern Avenue, University of Sydney (Camperdown campus)

1332nd OGM and Open Lecture

Professor Michael Blumenstein FRSN FACS (Pro Vice-Chancellor, Business Creation and Major Facilities) and Professor Nicholas Davis (Director, Strategy and Operations, Human Technology Institute) University of Technology Sydney, "AI: the Good, the Bad, and the Ugly," 4 June, Michael Crouch Room, Mitchell Building, State Library of NSW, Shakespeare Place, Sydney, https://youtu.be/CowilVO2W20

ATSE Sydney Event: June 2025

(Jointly with the Australian Academy of Technological Sciences & Engineering), Fiona Simson FTSE Vice-President, World Farmers' Organisation Chair, Food Systems CRC, Practising Farmer, "Feeding the world, the smart way," 11 June, Union University and Schools Club, 25 Bent Street, Sydney

Joint AIP, RACI, RSNSW, and ANSTO Event: June 2025

(Jointly with the Australian Institute of Physics, the Royal Australian Chemical Institute, and the Australian Nuclear Science and Technology Organisation) Professor Richard Garrett, SUPL Chief Scientist and ANSTO Honorary Fellow and Assoc. Prof. Tony Hooker, Centre for Radiation Research, Education, and Innovation University of Adelaide, "Journey to the Centre of the Earth: Unlocking Mysteries of the Universe," 17 June, Hybrid event: ANSTO Discovery Centre, New Illawarra Road, Lucas Heights

Southern Highlands Branch Meeting: 2025-5

Dr Hugh Mackay AO FRSN FAPS Social Psychologist and Researcher, "The Way We Are," 19 June, RSL Mittagong, Carrington Room

Lunchtime series: Provocations and Inspirations (June 2025)

Dr Cathy Foley AO PSM DistFRSN FTSE FAA, Chief Scientist of Australia (2021–2024), "The Productivity Challenge: the role of innovations and R&D in Australian business," 23 June, Union University and Schools Club, 25 Bent Street, Sydney, https://youtu.be/oTmVIzV5nvo

Western NSW Branch Meeting 2025-2

Distinguished Professor Jing Sun, Professor of Biostatistics, Rural Health Research Institute, Charles Sturt University, "Hidden causes of rising disability and death in the working population," 25 June, Live streaming, https://youtu.be/gVemR4HDzq4

Ideas@theHouse: June 2025

Professor Jason Sharples FRSN FTSE Professor of Bushfire Dynamics and Foundation Director, UNSW Bushfire UNSW Canberra, "Extreme wildfires in a warming world: insights and challenges," 26 June, Government House, Sydney, https://youtu.be/QQPbo1wZNGM

RSNSW Poggendorff Lecture 2025

Professor Alex McBratney AM FAA Professor of Digital Agriculture and Soil Science and ARC Laureate Fellow, School of Life and Environmental Sciences and Sydney Institute of Agriculture, University of Sydney, "Agriculture over the Horizon," 2 July , University of Sydney, RD Watt Building, https://youtu.be/9Hr5bu1fF5M

Joint Royal Australian Historical Society-RSNSW Event: July 2025

Dr Anne Coote, "Not just a gentleman's club: The origins and significance of the Royal Society of NSW," 16 July , History House, 133 Macquarie Street, Sydney

Southern Highlands Branch Meeting: 2025-6

Dr Michael de Percy FRSA FCILT MRSN Canberra Press Gallery Correspondent, *The Spectator Australia* and Editor-in-Chief, *Journal of Telecommunications and the Digital Economy*, "Stray Dogs and Gross National Happiness: Bhutan's Modernisation Challenge," 17 July, RSL Mittagong, Carrington Room

1333rd OGM and Open Lecture

Associate Professor Ian Wright, Discipline of Environmental Science, School of Science, Western Sydney University, "PFAS in New South Wales: Is it under control?" 6 August, Michael Crouch Room, Mitchell Building, State Library of NSW, https://youtu.be/oEhWrEmUyic

Lunchtime series: Provocations and Inspirations (August 2025)

Ross Gittins AM FRSN FASSA Economics Editor, The *Sydney Morning Herald*, "Solving Australia's Productivity Crisis," 19 August , Union University and Schools Club, 25 Bent Street, Sydney, https://youtu.be/J5aOm9ldRXo

Western NSW Branch Meeting 2025-3

Distinguished Professor Geoff Gurr FRSN, Professor in Applied Ecology, Gulbali Institute, Charles Sturt University, "Nature-based solutions for future farming," 20 August, Live streaming, https://youtu.be/m7XEDoFEM4k

Southern Highlands Branch Meeting: 2025-7

Professor Andrew Dempster, Director, Australian Centre for Space Engineering Research, School of Electrical Engineering and Telecommunications, UNSW Sydney, "Mining Water on the Moon," 21 August , RSL Mittagong, Carrington Room

Hunter Branch Meeting 2025-3

Laureate Professor Jennifer Gore AM FASSA, School of Education, University of Newcastle, "An elegant solution to enduring problems in education," 21 August, NEX, Newcastle Exhibition and Convention Centre, 309 King Street, Newcastle West, https://youtu.be/IkNnWHLCdVM

Ideas@theHouse: August 2025

Professor Bamini Gopinath, Cochlear Chair in Hearing and Health, Macquarie University Hearing, Faculty of Medicine, Health and Human Sciences, Macquarie University, "Busting Myths, Bridging Gaps: Public Health Approaches to Hearing Loss in Adults," 28 August, Government House, Sydney, https://youtu.be/Nj-lJfgkLIY

RSNSW Visits Program 2025-2

Australian Botanic Garden Mount Annan, 1 September, Australian Botanic Garden Mount Annan, 362 Narellan Road, Mount Annan

1334th OGM and Open Lecture

Emeritus Professor Peter Wells FRSN UTS Business School, University of Technology Sydney, "Bringing Financial Reporting into the 21st Century," 3 September, Live streaming, https://youtu.be/7zIreVvM3Zo

Southern Highlands Branch Meeting: 2025-8

Professor Fred Watson AM, Honorary Professor, School of Mathematical and Physical Sciences Macquarie University, "Tomorrow's Universe — the discoveries that will change science," 18 September, RSL Mittagong, Carrington Room

Australian Academy of Technological Sciences & Engineering Chaikin Oration 2025

Dr Sue Keay FTSE, Director, UNSW AI Institute, UNSW Sydney, "AI in Australia: Meeting the moment or seeing it pass by," 25 September, Union, University & Schools Club Sydney (UUSC), 25 Bent St, Sydney

1335th OGM and Open Lecture

The Honourable Bill Shorten (Vice-Chancellor and President, University of Canberra) in conversation with Professor Merlin Crossley AM FRSN (Deputy Vice-Chancellor, Academic Quality, UNSW Sydney), "Have universities become too political?" 1 October, Michael Crouch Room, Mitchell Building, State Library of NSW, Shakespeare Place, Sydney, https://youtu.be/iwmNvDlteJs

Southern Highlands Meeting: 2025-9

[Postponed] "PFAS in NSW — Is it under control?" The Southern Highlands Branch regrets to announce the postponement of the lecture until 2026.

Lunchtime series: Provocations and Inspirations (October 2025)

Professor Anthony Burke FRAIA, Professor of Architecture, University of Technology Sydney, "After the Crisis: a new Australian Dream," 21 October, Union University and Schools Club, 25 Bent Street

New England North West Branch Meeting: 2025-1

Dr Kyle Mulrooney, Co-Director, Centre for Rural Criminology, University of New England, Panellists: Sam Coupland, Mayor, Armidale Regional Council, Samantha Guilbert, Youth on Track PCYC Armidale representative, "Building resilient futures: Understanding rural youth through the lens of place, risk, and prevention," 29 October, NOVA, 122 Faulkner Street, Armidale, https://youtu.be/PgyVSDLNtwM

Hunter Branch Meeting 2025-4

RSNSW-Hunter Medical Research Institute Male Infertility Public Forum, Dr John Schjenken (University of Newcastle, HMRI), Dr Elizabeth Torres-Arce (University of Newcastle, HMRI), Dr Nathan Burke (University of Newcastle), Dr Aleona Swegen (University of Newcastle, HMRI), Professor John Aitken (University of Newcastle, HMRI), Dr Andrew Hedges (IVF Australia), Nick Allen-Ducat (Hit 106.9 Newcastle), "Male Infertility Public Forum," 30 October, NEX, Newcastle Exhibition and Convention Centre, 309 King Street, Newcastle West, https://youtu.be/sy_xTrvRO7c

Western NSW Branch Meeting 2025-4 (a joint presentation of Charles Sturt University and the Western NSW Branch of the Royal Society of NSW)

Professor Jane Quinn FRSN Professor in Veterinary Physiology, Gulbali Institute, Charles Sturt University, "Optimising yield, growth, and use of the '5th quarter' for Australian agricultural food access and market security," 5 November , CSU Riverina Playhouse, Wagga Wagga, https://youtu.be/SgdwAFo8-Io

RSNSW and Learned Academies Forum 2025

"AI: The Hope and the Hype," 6 November , Government House, Sydney, https://www.youtube.com/playlist?list=PLYFFwCGj2FIbTwehefdklMuzxrHTeGD92

1336th OGM and Open Lecture

Professor Katherine Boydell FASSA Professor of Mental Health and Director, Arts-based Knowledge Translation Lab Black Dog Institute, "Arts-based Community Interventions for Youth Mental Health," 12 November, Live presentation, https://youtu.be/DaVuFo3yCKc

Southern Highlands Branch Meeting: 2025-10

Dr Jessica Milner Davis FRSN Honorary Research Associate, University of Sydney, "Laughing at other people's pain: Why do we do it, and is it ethical?" 20 November, RSL Mittagong, Carrington Room

1337th OGM and Open Lecture

Dr Donald Hector AM FRSN Principal, Grassick SSG Pty Ltd, "A Future Made in Australia," 3 December, Michael Crouch Room, Mitchell Building, State Library of NSW

Hunter Branch Meeting 2025-5

Adjunct Professor Warwick Giblin FRSN FEIANZ Principal, ESE Justice, "Renewable Energy 101: What is being delivered in NSW's first renewable energy zone?" 4 December, NEX, Newcastle Exhibition and Convention Centre, 309 King Street, Newcastle West

Note on Gazetting

The Government Gazette of the State of New South Wales is managed by the New South Wales Parliamentary Counsel's Office and has published Government notices, regulations, forms and orders since 1832. It went on line in 2001 and since 2014 is only to be found at https://legislation.nsw.gov.au/gazette.

On the initiative of RSNSW Fellow Robert Whittaker AM FRSN, the Society approached His Excellency the Governor to formally gazette fellows of the Society. All current fellows were included in the first gazetting in 2018, and subsequently at the beginning of each year fellows elected in the previous year will appear in the Gazette.

As the Gazette of Friday 17 January 2025 says:

> "Her Excellency the Honourable Margaret Beazley AC KC, Governor of New South Wales, as Patron of The Royal Society of New South Wales and in furtherance of the aims of the Society in encouraging and rewarding the study and practice of Science, Art, Literature and Philosophy, is pleased to advise and acknowledge the election of the following as Fellows of the Society in 2024."

Fellows

Proven leaders and experts in their field, entitled to use the post nominal FRSN. Please note Professorial titles — including adjuncts, conjoint, and professors of practice — have been used where applicable. Details as to their field of expertise, their resident university (or universities) or institution may be ascertained from the Royal Society of New South Wales.

ARMSTRONG, Professor Christopher Alan PSM FRSN

BAKER, Professor Andrew FRSN

BENNETT MOSES, Professor Lyria Kay FRSN

BENSON, Professor Iain Tyrrell FRSN

BLUMENSTEIN, Professor Michael FRSN

BROWN, Professor Trevor Colin FRSN

CHOW, Professor Eric Pui Fung FRSN

CURROW, Professor David Christopher FRSN

DAVISON, Professor Alan FRSN

EVANS, Mr Ralph John Lancaster AO FRSN

GIBLIN, Mr Warwick Bruce FRSN

GRAY, Professor Peter Philip AO FRSN

HASKINS, Professor Victoria Katharine FRSN

HUANG, Professor Xufeng Feng FRSN

HUPPERT, Dr Julian Leon FRSN

JAGADISH, Professor Chennupati AC FRSN

JONES, Dr Sarah FRSN

KETHEESAN, Professor Natkunam FRSN

KHAN, Professor Stuart James FRSN

KING, Professor Robert John FRSN

LIN, Professor Chung-Wei Christine FRSN

LOY, Professor Clement Tien-Hui FRSN

MAHER, Professor Christopher Gerard AM FRSN

MCGILLICK, Dr Paul Emerson FRSN

MORTON, Professor Susan Mary Bennett MNZM FRSN

ROBERTS, Professor Timothy Kilgour AM FRSN

ROSAMOND, Professor Frances A. FRSN

SCHMALZ, Professor Gerd FRSN

SHARMA, Professor Ashish FRSN

THOM, Professor Bruce Graham AM FRSN

TURNEY, Professor Christian Stewart MacGregor FRSN

WAND, Professor Matt FRSN

WEAVER, Dr James Crofton FRSN

WELLS, Professor Peter Alfred FRSN

Distinguished Fellows

Those Fellows of exceptional distinction, entitled to use the post nominal DistFRSN.

BELL, Dr John Anthony AO OBE DistFRSN

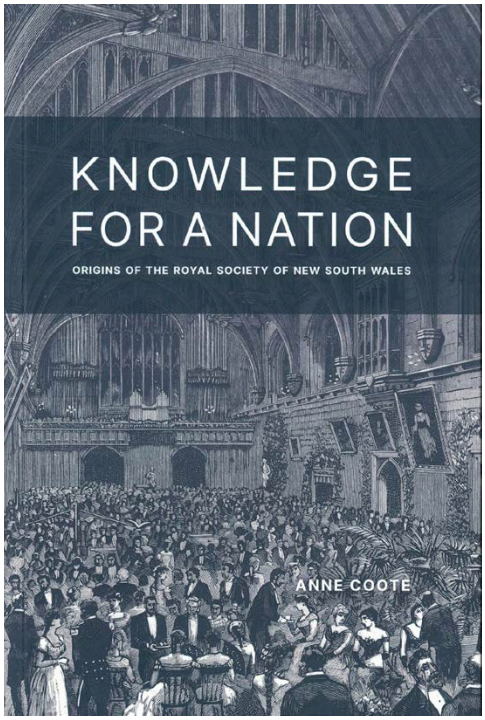
Knowledge for a Nation:
Origins of the Royal Society of New South Wales

Anne Coote
Royal Society of New South Wales
ISBN 978-0-64585-940-9

When Archibald Liversidge first arrived at the University of Sydney in 1872 as Reader in Geology and Assistant in the Laboratory, he had about ten students and two rooms in the main building. In 1874, he became Professor of Geology and Mineralogy and by 1879 he had persuaded the University Senate to open a Faculty of Science. He became its first Dean in 1882.

In 1880, he visited Europe as a trustee of the Australian Museum and his report helped to establish the Industrial, Technological and Sanitary Museum which formed the basis of the present Powerhouse Museum's collection. Liversidge also played a major role in establishing the A*ustralasian Association for the Advancement of Science* which held its first congress in 1888.

This book is essential reading for those interested in the development of science in colonial Australia, particularly the fields of crystallography, mineral chemistry, chemical geology and strategic minerals policy.



The book is available from the RSNSW online Shop at $50 for RSNSW members, or John Reed Books ($59.95).

The Royal Society of New South Wales

Information for authors

Details of submission guidelines can be found in the on-line Style Guide for Authors at: https://royalsoc.org.au/society-publications/information-for-authors

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If the file-size is too large to email it should be placed on a USB drive (or other digital media) and posted to:

The Honorary Secretary (Editorial),
The Royal Society of New South Wales,
PO Box 576,
Crows Nest, NSW 1585
Australia

Manuscripts will be reviewed by the Editor, in consultation with the Editorial Board, to decide whether the paper will be considered for publication in the *Journal*. Manuscripts are subjected to peer review by at least one independent reviewer. In the event of initial rejection, manuscripts may be sent to other reviewers.

Papers (other than those specially invited by the Editorial Board) will only be considered if the content is either substantially new material that has not been published previously, or is a review of a major research programme. Papers presenting aspects of the historical record of research carried out within Australia are particularly encouraged. In the case of papers presenting new research, the author must certify that the material has not been submitted concurrently elsewhere nor is likely to be published elsewhere in substantially the same form. In the case of papers reviewing a major research programme, the author must certify that the material has not been published substantially in the same form elsewhere and that permission for the Society to publish has been granted by all copyright holders. Letters to the Editor, Discourses, Short Notes and Abstracts of Australian PhD theses may also be submitted for publication. Please contact the Editor if you would like to discuss a possible article for inclusion in the *Journal*.

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