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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 and Proceedings*.

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Editorial: The unreasonable effectiveness of mathematics

Robert E. Marks

This issue has been produced during the pandemic. Although it is mainly a record of the Four Academies Forum, of last November, it also contains other papers — not least a timely paper by Graham Bell FRSN outlining a test for changes in taste (and smell) that might be evidence of infection by COVID-19. This test, although not definitive, can be performed at home, and might lead to further, more rigorous testing for any possible infection.[1]

In late June[2], the Society held its Annual Dinner, via Zoom. Four of us gathered chez moi to have dinner and watch proceedings. Brian Schmidt DistFRSN, introduced by the Governor, our Patron, Margaret Beazley, spoke on "Evidence and education in a post-truth and post-COVID world." The Governor's learned introduction, followed by Professor Schmidt's address, are both published here.

There is also a paper by David Hush FRSN, presented on the occasion of the world premiere performance, on 27 February 2020 at the Sydney Mechanics' School of Arts, of his Partita for Solo Violin, in the tradition of J. S. Bach and others. This piece was commissioned by the Royal Society, a first. As well as a discussion of the history of solo sonatas for violin, the paper includes hyper-text links to recordings of this performance by Anna Da Silva Chen, as well as a performance by her on the same occasion of Bach's Solo Violin Partita No. 1 in G minor BWV 1001. This is a departure for the *Journal*, although not the first article on music.[3]

Although memories of the smoke and haze have faded with winter and the pandemic, the fires last summer were horrific, lasting almost six months on the back of a fierce drought.[4] I was aware of Stephen J. Pyne, at Arizona State University, the doyen of writers on bushfires and wild fires. He has written several books on such fires in the U.S., Australia and elsewhere.[5] In particular, thirty years ago he wrote a book specifically on the history of bushfires in Australia, *Burning Bush* (1991). I had the idea of approaching him to commission a paper which might build on the 1991 book, in the light of last summer's fires. He was very receptive to my invitation, being on the point of publishing an op-ed piece on the topic in the *Guardian*.[6] More of a reflection on past and future fires, the paper here introduces the notion of the Pyrocene era,

1 Graham tells me that a pre-pub version of the paper has led to an invitation from the Japanese Association for Smell and Taste Science (JASTS) for their virtual conference in October.

2 June 27th, the 199th birthday of the Society.

3 See, for instance, David Hush. Reflections on Mozart. *Journal & Proceedings of the Royal Society of New South Wales* **151**: 209–212, 2018.

4 A weekend house of mine in the Blue Mountains was utterly destroyed four days before Christmas. The ashes of Olivia Newton-John's father, Brinley (1914–1992), are (still) buried on the property.

5 Sadly, my copies were incinerated last December. It's Kindle from now on for me.

6 Stephen J. Pyne, "The Australian fires are a harbinger of things to come. Don't ignore their warning, *The Guardian*, 7 January 2020. https://www.theguardian.com/commentisfree/2020/jan/07/australia-fires-warning

affecting not just Australia (although especially affecting Australia) but also California, the Mediterranean, to begin with, and then, one by one, increasingly flammable regions across the globe. Incidentally, I was not alone in thinking of Steve Pyne: an old friend of mine, Henry Rosenbloom, publisher of Scribe Books in Melbourne, also approached him. The result of some hard work across the Pacific is *The Still-Burning Bush* (2020).

Another departure for the *Journal* was the last issue, Volume 152, Number 3, March 2020. This venture, between the Royal Society and the Australian and New Zealand Associations of von Humboldt Fellows, includes papers from their 2019 Biennial Symposium at Macquarie University. David Black FRSN was the mid-wife to the venture. It is on-line only. Given the topic of the 2017 Forum[7] and Brian Schmidt's address here, of special interest is the piece by Dietmar Höttecke.[8]

Sadly, one of our Distinguished Fellows, Lord Robert May of Oxford, died earlier this year. Len Fisher FRSN, his old friend, has written an obituary. Lord May's prolific work in physics, biology, and ecology included a development that is very timely during the pandemic: he and co-authors derived the reproductive ratio for pandemics (an indication of the speed of spread of the infection), which we have heard much about recently. As the obituary notes, the May-Wigner theorem derives from theoretical work of May's on the counter-intuitive lack of stability of large complex eco-systems; Eugene Wigner (1902–1995) had proved this for systems in physics. But Wigner (1960) had remarked on the "unreasonable effectiveness of mathematics" in the natural sciences: "The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve." Bob May was one of the first to show that mathematics also serves this role in the biological and ecological sciences.

As for the Forum, it has stood out for me as demanding the most work of any of the four Forums I've edited. Of the sixteen presentations on the day, over six months later I have received only eight final papers. Yes, the corona virus has disrupted work patterns, but none of the recalcitrants mentioned the pandemic as a reason for their lack of response, if indeed they gave any. Since I see the *Journal* as a publication of record of the Society's activities, I here publish lightly edited the transcripts of the eight presentations, the papers for which are missing in action. The other eight papers are present.

There have been some changes to the Editorial Board. Following the appointment of Len Fisher FRSN last year, this year Jessica Milner Davis FRSN has joined the Board, and we thank the departing Michael Lake for long service to the *Journal*, first as Editor, and then as Editorial Board member, for over twelve years. Thank you to Jason Antony, as always. I also thank John Spence FRS for the epigraph from Eugene Wigner that began this editorial.

7 "The Future of Reason in a Post-Truth World," *Journal & Proceedings of the Royal Society of New South Wales* **151**: 22–105, 2018.

8 Dietmar Höttecke, Understanding science and how it works in the age of social media, *Journal & Proceedings of the Royal Society of New South Wales* **152**: 307–319, 2020.

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Evidence and education in a post-truth and post-COVID world

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Abstract

Professor Brian Schmidt AC FRS DistFRSN FAA and Nobel Laureate in Physics gave this address at the 2020 Annual General Meeting of the Royal Society of NSW on 27 June 2020. It was Zoomed. He was introduced by Her Excellency the Honourable Margaret Beazley AC QC, Governor of NSW.

Margaret Beazley:

It is my delight as your Patron to join with you tonight in celebrating 199 years of the Royal Society of NSW — the oldest learning society in the Southern Hemisphere.

The Royal Society's original name — the Philosophical Society of Australasia — and the Society's purpose of advancing and communicating knowledge, bring to mind Plato's description of the philosopher as concerned with the pursuit of truth: "not the changing world of sensation, which is the object of opinion, but the unchanging reality which is the object of knowledge."[1] Whilst, in the 21st century, knowledge develops exponentially, Plato's differentiation of sentiment from knowledge remains as a granite-like edifice in the pursuit of truth.

Plato's perception of the pursuit of truth is to be contrasted with what Winston Churchill perceived to be the essential pursuit of lawyers. As a lawyer, I know that law is concerned with the application of principle to found facts — which are the truth for that purpose. According to Churchill, however, lawyers "occasionally stumble across the truth, but most pick themselves up and hurry off as if nothing had happened."[2] But I digress from the timely topic upon which tonight's guest speaker, Professor Brian Schmidt, will speak.

In 2016, the word *post-truth* was the Oxford Dictionary's word of the year. Defined to mean "relating to or denoting circumstances in which objective facts are less influential in shaping public opinion than appeals to emotion and personal belie."[3] So defined, "post truth" describes a world which is the perfect inversion of Plato's philosopher. *Time Magazine* well understood this, pointing out that "post-truth" is where "feelings trump facts."[4]

None of this is new. Writing in 1967, philosopher Hannah Arendt observed in her essay "Truth and Politics," "the greatest antagonist of factual truth is an opinion,

1 Plato, 'The Philosopher and the Two Orders of Reality' *The Republic*.

2 Attributed to Winston Churchill, "Picturesque speech and patter," *Reader's Digest* 40 (April 1942) 92.

3 Oxford University Press, "Word of the Year 2016" https://global.oup.com/academic/content/word-of-the-year/?cc=au&lang=en

4 Kelly Steinmetz (2016) "Oxford's word of the year for 2016 is *post truth*" *TIME Magazine* (online, 15 November) https://time.com/4572592/oxford-word-of-the-year-2016-post-truth/

[not] a lie."[5] And in 1992, Serbian American playwright Steve Tesich, who is credited with popularizing the term "post-truth" in his essay "A Government of Lies," criticized the public for submitting to a world "where truth was no longer important or relevant."[6] The President at the time was George Bush, snr.

For the philosopher, no less than every person who seeks to be an engaged and informed member of our society, it is concerning, if not chilling, that what this 2016 word of the year represents has become part of our contemporary Zeitgeist — where mass communication has enabled a discourse in which experts are "perceived as a cartel of villians,"[7] where experts are disregarded in favour of those whose popularity or celebrity provides a platform from which to proffer "their" opinion[8] — invariably subjective and emotional — which is "truth," at least for that day.

An MIT study, published in 2018, analysed English language news stories tweeted from 2006 to 2017. The study found 126,000 false news stories were re-tweeted by just over 3 million people, more than 4.5 million times.[9] The top 1% of false-news tweets "routinely diffused to between 1,000 and 100,000 people" — at six times the rate of the truth.[10] The most common categories of false-news, were, in order: politics, urban legends, business, terrorism & war, science & technology, entertainment and natural disasters.

The current coronavirus outbreak, COVID-19 — or "Rona" as it is more colloquially referred to on Twitter[11] — has demonstrated both the sheer devastation that a post-truth discourse can have and the strength of its counterpart — "researched truth" — by which I mean evidence-based information.

In this regard, Australia's response to COVID-19, has been careful, vigilant and impressive. The Government has based its policy and decision-making on infection rates, sources of infection, scientific research and modelling.[12] And, importantly, the focus of social media in this country has been on the provision to the community of government and health-based information, not the provision of someone's mere opinion.

It can readily be seen that reliance upon "evidence" by decision makers is thus inherently valuable. One only needs to utter the words "disinfectant" and "a sort of

5 Hannah Arendt (1967) "Truth and politics" *The New Yorker* (25 February) https://www.newyorker.com/magazine/1967/02/25/truth-and-politics

6 Yael Brahms (2020) "Philosophy of post-truth" *Institute for National Security Studies*, 1.

7 Matthew D'Ancona (2018), *Post-Truth: The New War on Truth and How to Fight Back*, Ebury Publishing.

8 Nick Enfield (2017) "In a post-truth world, who can we believe?" (17 November, online) *University of Sydney* https://www.sydney.edu.au/news-opinion/news/2017/11/17/we_re-in-a-post-truth-world-with-eroding-trust--it-can-t-end-wel.html

9 Soroush Vosoughi, Deb Roy and Sinan Aral (2018) "The spread of true and false news online" *Science* 359(6380): 1146–1151 (9 March) https://science.sciencemag.org/content/359/6380/1146/tab-pdf

10 Robinson Meyer (2018) "The grim conclusions of the largest-ever study of fake news" *The Atlantic* (online, 8 March) https://www.theatlantic.com/technology/archive/2018/03/largest-study-ever-fake-news-mit-twitter/555104/

11 https://twitter.com/hashtag/rona?lang=en

12 See, e.g, Johns Hopkins University & Medicine *Coronavirus Resource Center* https://coronavirus.jhu.edu/map.html

cleaning,"[13] to say nothing of the reported observation that "if we stop testing, we'd have fewer cases," to appreciate, indeed cringe, at the difference.

So, in a post-truth, post-COVID world, it has never been more essential to know and understand the evidence, as decisions are made in respect of education for the immediate and near future — decisions which will have a lasting impact on the present and upcoming generations, decisions which cannot lose sight of what "education" is.

In Trent Dalton's debut novel, *Boy Swallows Universe*, there is an exchange between Robert, the dissolute father of the two boys around whom the story revolves and the school counsellor.[14] The father, the usually drunk, sad wreck of a man but who, perversely, reads widely, says to the counsellor, "Educating the mind without educating the heart is no education at all." He references the quote to Aristotle, as the stunned counsellor nods in agreement, saying it is the mantra by which she lives.

Researchers doubt the attribution but do accept that Aristotle likely said that "teaching is powerless without a foundation of good habits." John Dewey, the American philosopher and educator was of similar mind. On the title page of Tara Westover's memoir *Educated*, appears this quote from Dewey, "I believe … that education must be conceived as a continuing reconstruction of experience; that the process and the goal of education are one and the same thing."[15]

May I again wish the Royal Society of NSW a very happy 199th birthday and congratulate the 2020 Award winners as we all settle back and listen to our eminent and erudite guest speaker, Professor Brian Schmidt, the Vice Chancellor of the Australian National University, as he speaks to us on "*Evidence and Education in a Post-Truth and Post-COVID world*". — Margaret Beazley

13 https://www.youtube.com/watch?v=zicGxU5MfwE

14 Tent Dalton (2018) *Boy Swallows Universe*, Harper Collins, 302.

15 Tara Westover (2018) *Educated*, Penguin.

The Address

If there is one thing that the motion of democracy has made me better understand over the past few years, it is the rise of Fascism in Europe after World War I. How could a whole country do things that were so crazy and so horrible — I never understood it. I still don't understand it, but I now know how it can happen — and it all comes from playing with people's minds and values by the information they receive.

The Germans, under Goebbels' leadership, produced the propaganda playbook which was used in the years after World War II by non-democratic governments around the world to control their people.

But, in the years after 1945 — despite a protracted Cold-War that had huge negative effects to people outside the central players — the open democracies, capitalism, and the emergence of technology ultimately crushed the alternative forms of government from having significant power. The decisive end was on 9 November 1989 with the symbolised fall of the Berlin Wall.

With this event passing, a highly interconnected globalised society emerged — with human life expectancy rapidly rising, and poverty rapidly falling across the world. After 100,000 years humans had finally — it seems to me — learned to work *en masse*, largely for the collective good. This is not to say it was perfect everywhere, but it was the broadest-scale improvement for humanity as a whole in our history.

And, in my lifetime, a lot has changed. In my childhood (and I am only 53 years old), China has had mass starvation and malnutrition, but in recent decades it has seen a rapid economic shift by embracing western capitalism, and driving the mass production of increasingly less expensive consumer goods to more and more of the world. China's relatively low labour costs, coupled with their rapid increases in productivity and associated resource boom, has largely led to Australia's economic prosperity, and only now are we seeing an end to a 28-year period of growth.

In the time immediately following World War II, the research and the technology that emerged was front of mind for everyone. University-trained researchers led many of the biggest discoveries and scientific breakthroughs of the 20th century. They discovered penicillin — and Howard Florey later became ANU Chancellor. Mark Oliphant, a founding ANU physicist, led a team in England to develop the foundations or radar; and then went on to help with centrifuge uranium in Oakridge that led to the creation of a nuclear bomb. Kenneth Le Couteur, another founding ANU physicist, worked alongside Alan Turing who cracked the Enigma Machine. And of course, a vaccine for polio was developed saving millions of people around the world. Percival Bazeley who worked in Salk's lab, returned to Australia to run the Commonwealth Serum Laboratories (CSL). CSL are of course, currently working on a COVID-19 vaccine which will be available in the (hopefully) not too distant future …

Scientists were king in the 1950s. Their education, associated knowledge and the evidence they applied to the problems of the world were highly regarded both in the West, and, of course, in the Soviet Union.

Every year, more and more people were involved in technologically-underpinned pursuits. In the space race, nearly 6 per cent of US government expenditure was spent "to get a Man on the Moon" — and the Cold War created a huge investment in defence-related technology. To some, this might be seen as a waste of money. But I disagree — the economic and other positive spill overs to society were enormous …

Higher Education became something children in the upper half of the income distribution aspired to, rather than the upper half per cent — and universities around the world grew in size although, unfortunately, not necessarily in stature. In the pinot noir business (also one of my trades), if everyone can afford your wine, it is, almost by definition, not perceived as being very good, no matter the quality.

And technology, based on the basic research of universities, increasingly emerged out of corporations (rather than universities and government labs). These entities became huge when they created something everyone wanted, and entrepreneurial billionaires who were usually educated — or partially educated at university (noting some very famous dropouts …) — became (and still are) the new technological heroes.

So we are now in a time where it is not so much the researchers, but rather the innovators who are seen as important figures by the public. It not the people or organisations as much who invented the technologies, but rather the innovators who converted those ideas and became rich.

But research did continue — and at pace across the world — but in a more anonymised form. Huge research teams found the particles that vindicated the standard theory of particle physics; sequenced the Human Genome; and detected Gravitational waves. They also greatly increased agriculture efficiency and improved public health. Life expectancy for people around the world has risen from 46 years in 1950 to 72 years today. In 2015 less than 10 per cent of the world was living in extreme poverty, down from 42 per cent in 1981, when the current measure was first introduced.

In 1991, Tim Berners-Lee, who was part of one of those big anonymised teams at CERN (and whose mother Mary Lee Woods worked at Mt Stromlo Observatory at ANU where I work — again emphasising how connected our universities really are to the events that have shaped the century) invented the world-wide-web.

This invention enabled the internet — developed out of DARPA in the USA and widely used in the research community — to be used by anyone and everyone to easily exchange information. I remember the day that "WWW" was effectively born for me (and for the world). In 1993, when Mosaic[16] — the first graphical browser — was released for UNIX, I downloaded it using Gopher[17] (the internet pre WWW). I made my own web page on that first day and I watched the world wide web grow exponentially across the research community, and in the following months explode into mainstream life.

16 https://en.wikipedia.org/wiki/Mosaic_(web_browser)

17 https://en.wikipedia.org/wiki/Gopher_(protocol)

I believe this day in 1993 — April 22 — is the day of my life where the course of the world changed more than any other.

A big call, but on that day, information became shareable between everyone in the world — not immediately of course, but shareable.

Before that day, facts were found in books in libraries — the information in them was curated by expert academics around the world and in democracies reported by a free press. In democracies the academies and the press were self-regulated with power and influence related to the perceived quality of the knowledge, analysis and reporting.

In 2020, while prestige in the academy and press still flows from quality — the power and influence of elite institutions is slowly being overwhelmed by the ever increasing din of information on the internet.

In 1993 I was excited. I could see the promise. Everyone finally has a voice. Everyone has access to the world's knowledge. It will be impossible for institutions or individuals to avoid transparency.

But even in 1993 I already could see some emerging issues. With so much information, how do you find what was interesting? And, geeze, there was a lot of junk … I lived through the World Wide Web Wanderer[18], then Infoseek[19], then WebCrawler[20], then Lycos[21], Excite[22], AltaVista[23] and HotBot[24].

18 https://www.oxfordreference.com/view/10.1093/oi/authority.20110803124909395

19 https://en.wikipedia.org/wiki/Infoseek

20 https://en.wikipedia.org/wiki/WebCrawler

21 https://en.wikipedia.org/wiki/Lycos

22 https://en.wikipedia.org/wiki/Excite

23 https://en.wikipedia.org/wiki/AltaVista

24 https://en.wikipedia.org/wiki/HotBot

AltaVista and HotBot were my go-to search engines which I became expert at using — and then there was that day, I was told about Google in 1998, while on an observing run in Hawaii — it was so much better than everything else, and the rest is history …

Google was very good because it found what I wanted — and indeed it has continued to deliver on that promise using more and more clever algorithms in the 22 years since I first used it. But there is a problem — what if I have a prior belief on let's say, climate change …

These search engines help me sift through the internet and find the information I want. So if I believe climate change will boil the oceans this century, or that climate change is a fabrication of the deep state to enslave humanity — I will be preferentially connected to that information that help confirm my prior belief. Even if the search engine is made to be completely agnostic, most people's brains will select and connect to the information they already believe. And the world-wide-web allows anyone to put up anything they believe or want to believe. The curation of information by experts — as old as humanity itself — has been upended.

But it gets worse! Imagine you want to convince people to your way of thinking — why not flood their world with your story, even if not exactly true. Or why not be cleverer, and nudge people slowly but surely — moving their point of view by tailoring the information they receive over time. Behaviour psychology and economics works! Perhaps a bit too well.

And what if you want to create discord in your enemy — flood their information channels with polarising information about other people in their society. And with more and more information aggregated on the web from people's phones, emails, social media accounts, public information, credit card records — a clever institution's ability to understand how individuals tick and manipulate people *en masse* should not be underestimated.

In this regime, what is a fact? What is the news? What is truth? Facts and news — which we used to take for granted from what was in the encyclopædia or in a decent newspaper — were actually carefully curated by our academics and free press. All of the ambiguities were carefully sorted out by highly trained experts largely behind the scenes of the average citizen.

And how does democracy work when there is no longer an agreed set of facts or news? Where intentionally deceptive information is rampant, and where we come into contact with polarising material via multiple streams every day. And how does democracy defend itself against totalitarian states where information, instead of being allowed to run rampant as part of personal freedom, is carefully controlled and used to control people to the states' desires? My observation is, not very well …

And this is the world I saw as 2019 finished. The COVID-19 pandemic, for all the death, pain, and disruption it is causing, perhaps provides the opportunity to reclaim, at least partially, the ascendancy of truth, knowledge, expertise — of course, if we do not descend into anarchy first.

Why do I say this? In 2020, expertise and knowledge have showed their strength in a way that the tools of misinformation and disinformation cannot compete, and where those who are in power, and uninformed, have been left wanting, and unfortunately with tragic consequences in many cases.

Here in Australia we did not listen to the advice of fire experts last year around the coming fire season and prepare as we should have. Now, there is only so much one can do in a year like this one. But we could have done more, and less destruction would have resulted, and that is something that there is a consensus view of in the community, that could not be plastered over with spin and misinformation.

But in the same vein, Australia has largely listened to its health experts, and we find ourselves in a state that is much better than most of the world in dealing with COVID-19 — although I note it is a long journey ahead. And I know there will be cynics out there on many sides, but from the first decision to close the border, to a moderately hard lock down, to our current re-openings, and to our economic response — the Prime Minister has listened consistently to the expertise of the Chief Medical Officer (CMO) and the Secretary of Treasury. His popularity has soared, and Australia has benefited by being in a much better state than most other places. I have been careful throughout the pandemic to listen to the experts, and not become an arm-chair epidemiologist. Although I will say I still do ask them lots of questions.

It turns out not taking expert advice can really do real harm. We only have to look at my homeland of the United States and [as of 6 June] the 130,000 people and counting who have died there, to see how big a difference it can make. And seeing the effect of ignorance is making believers — at least temporarily — out of voters. In our democracies we must find a way to support evidence-informed decision making of our politicians, and not re-normalise the spin, hyperbole, and the "whatever it takes to get elected" over "what's good for our nation" approach to business as usual.

So we have a chance, now, for our political leaders of all sides — federal, states and territories — to undertake a course correction for our democracy. But there are some key ingredients.

First of all, we need a commitment by political leaders that winning the next election is secondary to what is right for the nation. And that means acknowledging appropriate evidence when making decisions, even if political compromise is necessary. And when decisions are changed to improve the situation based on evidence, we need to applaud these decisions, rather than berating them as a sign of weakness in our leaders. We, as leaders in the community, need to stand up for good behaviour and decision making of our politicians, even if we disagree with their ultimate choices.

Education is the foundation of successful nations. We need to take a fresh look at our kindergarten to year-12 education system and ask if we want a system that increasingly separates people into different schools based on their culture or socio-economic status. Where I grew up, we all went to the same school — rich kids, poor kids, black kids, white kids, Muslims, Catholics, protestants, and atheists, immigrants, indigenous … you name it. And that was good for me — it was good for everyone … Going to school is not just about scholarly learning, it is also a time to build up a shared value set within the community. We need to ensure our nation grows with a more universal set of principles, rather than one where the identity of the country fragments into multiple value sets, and, in turn, leads to multiple conflicting truths.

Education is the great equaliser. And while I can appreciate the efforts to equalise funding based on need as an improvement of the current system, I think it is as true as in 1954 when the Supreme Court of the US ruled unanimously that "separate education facilities are *inherently* unequal."

My views here are not main-stream Australian on this point — and I don't blame any parent for wanting to do what they think is best for their child. But supporting individual parents to do what they think is best for their child has societal consequences. And these consequences are now amplifying. For a successful and prosperous Australian democracy, we need a highly educated population, with a shared set of values, that creates a level playing field so that the talents of the nation can most appropriately be nurtured. The current system is underperforming on multiple fronts.

The Higher Education sector has been hit hard by the COVID-19 crisis, and we have a chance to reset the status quo and make sure our system serves the Australia of the future — rather than be a patchwork of ideas quilted together from the past.

I think we need to think hard about what we want out of our TAFE and university sector. For me, it is making sure that every Australian has access to higher education throughout their working lives that enables them to be productive, and, taken together, gives Australia one of the world's most productive workforces. This system needs to provide the foundational education that underpins a life's work, as well as the specific skills that will need to be continuously updated across someone's working life. So this means getting our TAFE system up and first rate — let's look to Switzerland for inspiration. But, also, Australian business have to be highly integrated and invested in TAFE for this to work. And it has to cover a vast range of employments, from basic training all the way up to highly skilled technical skills — and it needs to be open for people for their entire lives. That is how to remain relevant and productive in the modern world.

And for universities, let's start by making sure our students and their education are outstanding. I'd like to be able to spend a bit more money on our students actually. Right now for example, for one of my Law students may well have come from a private Sydney school where last year their fees were $38,000 and the government topped it up with an additional $3,800. For me to educate these same students, a year later — and, may I add, support a Law faculty in the world top-20 — I get $11,000 from the student, and $2,160 from the government. But even if you are from, for example, Queanbeyan High, the total support per student there is in excess of $20,000 — still more than 50 per cent of what a university gets. In principle, I could use my international student fees to help fund the education program (and I do — as I do not cover my costs educating my Law students), but I think the halcyon days where international student fees fixed deficiencies in our university funding system are largely over. And don't even get me started on how this impacts the Australian research endeavour. But that is for another talk …

The globalised world will be forever changed in the post COVID-19 world. It will be a long time before nation states will allow themselves to be so dependent on the world outside their borders. For Australia, as a highly open economy, this will have profound consequences on what we need to do next. But we are going to need to be more self-reliant — and I think that means protecting our democracy and its underpinning institutions.

At the beginning of the year, The ANUPoll asked Australians about their level of trust in a whole range of groups and organisations. Universities and schools were at the top of the level of trust, but at the bottom was the press, banks, and politicians.

A free and trusted press is a critical part of a successful democracy. The press are cornerstones of reporting news and reporting information in real time. And if we are going to sensibly use evidence in a post-truth and post-COVID world, we need to sort out the press.

If only 20 per cent of the country trusts the press, it is no wonder we are in a post-truth world. To make matters worse, the disruption of the business model of advertising by Google and other service providers on the internet has killed the financial viability of most people's sources of news. But there are successes in the disruption. *The Economist*, the *New York Times* and *Washington Post* — who go to huge global markets — represent the high quality that people are prepared to pay for. What is still unclear is how to get something that will serve everyone appropriately. Ideally, people will pay for quality content, but why do so, when you can read and hear what you believe on the internet, for free?

I fear we may need more regulation. Perhaps where the word "news" is reserved for a certain standard of journalism. A strong public broadcaster is another approach. But how do we get people to avoid fake news? I think it all comes down to education around how to interrogate information. It needs to be embedded in our curriculum from kindergarten onwards — not just what the facts are — but also how to learn how to decide if something should be believed, and making it a personal responsibility to not be fooled by misinformation.

In the post-truth and post-COVID world. I see three paths for nations.

One where the citizens of a nation get a more and more fractured set of information, where prosperity plummets and chaos rises, and where local bullies oversee an increasingly dysfunctional world. Let us call this the Mad Max Path[25].

My second path is where the citizens get a more and more controlled set of information. Where the truth is coherently manufactured to manipulate the majority of the citizenry and bring harmony to the population. Outliers are dealt with in a way that might seem unseemly to us, but prosperity increases, albeit more and more slowly over time under the careful control of the centre. Let's call this the 1984 Path[26] (noting the citizens live in the superstate of Oceania in this future) …

My third path — not surprisingly my favourite — is where citizens access and use more and more accurate information over time. A vibrant democracy flourishes, prosperity increases as the citizenry take risks, make mistakes, but learn more and more as they bumble along. But, they get where they need to go, a better place not pre-specified, in the end. Let's call this The Dish Path[27].

If we are going to shoot for the Moon and take the Dish Path, we need an education system that enables all of our chil-

25 https://en.wikipedia.org/wiki/Mad_Max

26 https://en.wikipedia.org/wiki/Nineteen_Eighty-Four

27 https://en.wikipedia.org/wiki/The_Dish

dren, regardless of their background, to interrogate information. We need a Higher Education sector to educate and train its students to the best of their ability in skills, knowledge, and problem solving. We need a university and research sector that creates new knowledge from which ideas that improve life will flow. We need a trusted media sector that reports information and news with a high degree of fidelity and rigor, and we need a political class who are prepared to use evidence and information to do what is right for Australia. And if they don't, the population will have the information and nous to hold them accountable. A truly virtuous cycle.

Thank you everyone, I hope my thoughts tonight are provocative.

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Olfactory acuity test while pre-symptomatic for COVID-19

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Abstract

An easily-constructed and self-administered olfactory acuity test for pre-symptomatic indication of infection by COVID-19 is described. This paper offers a simple test of smell threshold, which can be made and conducted at home and re-tested on oneself or others sharing isolation, and producing numerical data to indicate whether smell ability has decreased. During the COVID-19 pandemic, and until a vaccine is developed and available, becoming aware immediately of a loss of the important chemical sense, olfaction, can signal sufficient concern in individuals to self-isolate for the requisite period. The risk of COVID-19 spreading through communities can be reduced by promoting smell awareness by everyone, using simple, inexpensive measures, suggested in this paper.

Introduction

Recent clinical reports indicate that a high proportion of COVID-19 patients experience smell loss (anosmia), partial smell loss (hyposmia) and/or taste loss (dysgeusia) (Bagheri, et al., 2020; Carney, 2020; Meixner, 2020; Philpott, 2020; Roberts, 2020). Despite these reports being mainly anecdotal, support for a call for anosmia to be treated as a symptom of COVID-19 grew in the early months of the pandemic (O'Donovan et al., 2020, Gane et al., 2020).

Ear, nose and throat physicians in the UK, USA and elsewhere were very concerned by medical reports that smell loss and resultant dysgeusia are symptoms of COVID-19 infection, heralding important potential for reducing spread of the virus and early testing of those not showing other symptoms (Lewin, 2020; AAO-HNS, 2020).

New loss of smell or taste has become an officially recognised symptom of COVID-19 infection by the U.S. Centers for Disease Control and Prevention (CDC) (Fritz et al., 2020; Rashid, 2020). Supporting the CDC announcement has been a stream of reports by medical practitioners emphasising the prevalence and importance of the symptom occurring often before any other (Lutz, 2020, Hopkins and Kumar, 2020; Miller et al, 2020). Data from recently published surveys of large numbers of people, showed that chemosensory disturbance of olfaction (smell), gustation (taste) and chemesthesis (cooling or burning sensations carried by the trigeminal nerve), without blockage of the nasal passages, is common in at least two thirds of people testing positive for the virus (Menni et al., 2020; Parma et al., 2020). These findings render obsolete the earlier assertions by the UN World Health Organisation (WHO) that loss of smell or taste is a not a symptom of COVID-19 (Ault, 2020; Meixner, 2020) or is a "less common" COVID-19 symptom (Sae, 2020). After a relatively long period of ignoring the chemical senses, the U.K. health authorities announced acceptance of loss of smell or taste as a "key symptom" (Boyle, 2020; Bundock, 2020). In contrast, Australia changed minimally, listing loss of smell or taste as "less common".

Of crucial importance for managing the COVID-19 pandemic is the possibility that smell loss can begin as the only symptom in a person who is otherwise well (Carney, 2020). That person might be an unaware carrier and potential spreader of the virus. By detecting the loss of smell acuity as early as possible, society is better armed to defeat the virus.

The significant change in official position of health authorities in the U.S.A. and U.K. should go some way to reducing cases going undiagnosed and spreading the virus in people with no other symptom but loss of chemical sensory perception (Boseley, 2020; Fahey, 2020).

A loss of smell sense often accompanies nasal congestion with common colds and influenza, and can have several other causes, including hay fever, sinusitis and head injury. Sudden or unexpected smell loss, particularly in the *absence* of other symptoms such as raised temperature and cough, should be taken seriously by both citizens in communities at risk, and by clinicians.

A symptom of COVID-19, anosmia, offers the opportunity for easy self-monitoring by people currently self-isolating or "locked down."

Remote physical examination is now a common feature in the medical approach to the COVID-19 pandemic and it is recommended that patients take readings from instruments they have at home, including temperature, pulse, and blood pressure (Greenhalgh et al., 2020). These authors also note that loss of appetite (indicating possible dysgeusia) occurs in many patients and that anosmia is widely reported anecdotally as a common and early symptom of COVID-19 infection. Testing for smell loss can be added to remote physical examination by means described here.

This paper offers a simple test of smell threshold, which can be made and conducted at home and retested on oneself or others sharing isolation, and producing numerical data to indicate whether smell ability has decreased.

How can anosmia be measured?

Several rough screening methods are available for people wanting to self-monitor for changes in smell ability:

- *Introspection*: Sniff any household item or plant part that you know has an odour. Is your expectation met? If not, try another and another. This can be repeated at intervals, say at mealtimes or while gardening. If the items are not delivering their usual smell experience (orthonasal olfaction), there is reason to be concerned: contact your medical professional and request a COVID-19 test.
- *Perform the "jelly-bean test"*: Hold your nose and pop a jelly bean (or small piece of food or candy) into your mouth. With the nose blocked, all you should perceive is sweetness and perhaps some sourness or saltiness. Release the nose and immediately the flavour (orange, raspberry, etc) is perceptible (retronasal olfaction contributing to flavour perception). This test can be repeated at intervals to monitor onset of anosmia. If the return of flavour is not experienced, then there is reason to be concerned: contact your medical professional and request a COVID-19 test.

Early onset of anosmia can also be monitored to improve early detection of viral infection. Fundamental ability to detect a very faint odour can be determined as a change in smell detection threshold. This provides a more sensitive method than introspective sniffing or the jelly bean test.

There are two available test kits for measuring smell threshold used by clinicians:

1. An olfactory threshold test developed by Sensonics International (Snap & Sniff®): It involves a set of 20 tubes ("wands") containing systematically diluted odorants, including tubes with no odour, such that a person's odour detection threshold may be determined as a numerical score based on the point in the dilution series at which a smell cannot be detected. This kit currently sells for US$1259.
2. The "Sniffin' Sticks" olfactory threshold test available from Burghardt, Wedel, Germany: It also involves a set of pen-like odour dispensers containing a systematic dilution series of either of two odorants: n-Butanol and 2-Phenylethanol (Hummel, et al., 1997). Numerical scores are obtained and compared with data obtained from heathy people and those with clinical conditions. The two forms of the test sell for €334 and €471 respectively.

While useful, these tests are intended for clinicians. Clearly, what is needed in the COVID-19 crisis is an inexpensive, easily constructed, self-administered smell detection threshold test which would provide numerical information over repeated tests, and thereby show up a sudden or emerging pre-clinical onset of anosmia. Such a test is described here and is affordable for most people.

The "Ozzie" smell detection threshold test

Aim of the test

The test intends to measure an individual's olfactory threshold, and whether it is changing, by having the person sniff a series of odours decreasing in perceived intensity, by

Figure 1: Examples of the test materials with sample jars (12 needed) and items that could be used to make the primary test solution (rose water, orange blossom water, lemon or lime rind using the grater shown).

half in each sample, to zero (no odour). It is not intended to give a comparison against a population norm. Why? Chemical sensory science has shown that there is great variation (orders of magnitude differences) within individuals for a specific odour molecule and between species of molecules. What is intended here is to measure one person's threshold for a random smelly molecule and see if that value changes upon retest. Those values, for that person, are important.

In order to make this test easy to construct and self-administer, while remaining valid, strict methodologies used in sensory psychophysics can be overlooked. What is crucial is for you to find a numerical value for your detection threshold that you can then assess. What is required is that an unskilled person can make and obtain scores for themselves to tell if their ability to smell is changing detrimentally during the COVID-19 crisis.

	Jar No.											
	1	2	3	4	5	6	7	8	9	10	11	12
Odorant (mL)	100	50	25	12	6	3	1.5	0.8	0.4	0	0	0
Equivalent to:							32 drops	16 drops	8 drops			
Water (mL)	0	50	75	88	94	97	98.5	99.2	99.6	100	100	100

This test will give better information to the user than the jelly-bean test or sniffing random items in the house or garden because a threshold test addresses basic sensory sensitivity in numerical terms. The value of this in-home test, is *to find smell loss as soon as it starts to happen*, under COVID-19 social distancing and isolation, so that further action to prevent COVID-19 spread and its consequences can follow.

Test materials

- 12 small jars or bottles. They should have lids, wide mouths, be clean and dry and be identical in size and appearance. In the example described here, the jars (150mL) were bought from a homewares supply store ("two dollar" shop) and cost AUD$1.50 (approx. US$0.80 or one €) a piece. You can use the small jars (identical ones) you have collected in normal kitchen activity.
- A volumetric jug or measuring flasks for liquid marked in mL (optional)
- An eye dropper (optional)
- Another jug for filling the jars with water
- A marker pen that can write on glass
- A ruler
- Approx. 200 mL of *the primary odour solution*. This should be a clear water-soluble liquid which has a medium-strength, recognisable odour. In the example described here, a 200 mL bottle of Rose Water was obtained from the family pantry. Other flavour essences, or herbal infusions, could be made up in a water solution as the primary solution. Avoid any substance with a strong pungent "smell" such as alcohol, chilli, peppermint, oil or bleach. On no account must this, or any other sniff sample be sipped or drunk. Do not use anything poisonous, corrosive or flam-

mable. Your choice of primary odour is ideally of something pleasant smelling, lacking in pungency (sting) and mildly intense in its undiluted form.

- Two sheets of kitchen paper towel
- Pencil and paper for recording results

Making the serial dilution of odorants

Write the numbers 1 to 12 on the bottom of each jar and place them in order on the table.

The jars must be large enough to take the liquids and leave a couple of centimetres for the headspace (the gap between the lid and the liquid) which will contain smelly molecules released by the liquid.

Figure 2: Jars 1 to 12 filled with a dilution series of odorant solution — in this example, rose water.

Fill the 12 jars with the primary odorant solution and/or clean water jars using the measuring jug/flask and eye-dropper, as shown in the following table (based on a total liquid of 100 mL/jar):

Pen-and-ruler method

No volumetric measurement tools will be needed:

Mark the glass with the marker pen to show where to fill them with odorant solution and water. Using the black pen, mark the sides of the jars with a dot to indicate the top (maximum) level of the final solution for each jar. Simply choose the level that suits your jar and amount of primary solution available. The top level does not have to represent an exact volume, but all bottles should have the same top level. Leave a centimetre or two for the headspace between the top level and the lid.

The headspace is important *because you will be sniffing the molecules in the headspace.*

There will be four jars (Numbers 1, 10, 11 and 12) with only the top-level mark. Set these aside once the top level is marked onto them.

Figure 3: The 12 bottles, shuffled and ready to begin the test. The paper towel behind the jars shows where to place the jars after judging them.

The other jars will have a second (dilution) mark denoting the fraction of primary odour solution they will need. The fraction reduces by half with each successive jar. That is, after Jar 1, each successive jar, from 2 to 9 will have half the amount of primary odour solution of the preceding jar. So, Jar 2 will have a second mark showing half the amount of Jar 1; Jar 3 will have a mark showing half that of Jar 2, Jar 4, half that of Jar 3, and so on to Jar 9. Use the ruler to help set these dilution marks.

The marks for Jars 7, 8 and 9 will be so close to the bottom of the jar that exactness will be difficult. This doesn't matter greatly. What does matter is to halve the amount of primary odorant going into each jar as you progress down the series.

Jars 10, 11 and 12 will have only the top level indicated and these will be filled to that level with clean water at room temperature. These are your blank controls. If you can smell something in these, the jar is not clean, or the water is not pure.

Filling the jars: Next, for Jar 1, fill it to the top level with your strongest odorant (the primary odour solution). Then add half that amount of primary solution to the next jar (No 2), reducing by half the amount for each successive jar (jars 2,3,4 … 9). At the higher jar numbers (7, 8, 9), estimate the number of drops to be added: halving the drops as the jar number becomes higher. If you estimate that Jar 6 received 20 drops of primary solution, then deliver 10 drops to Jar 7, 5 drops to Jar 8 and 2 drops to Jar 9. Use an eye-dropper or carefully tilt and pour drops from the primary solution container.

When jars 1 to 9 have their sample amounts in them, *add clean water* to bring the solution in each up to the top level.

Figure 4: Test subject performing the olfactory threshold detection test ("Ozzie").

Whichever method you have used, all jars should now look identical. Rub off the lower level dots to remove clues to what the jar contains. Put a few marks and squiggles around the numbers under the jars to disguise the identity of the jar (if visible through the glass when sniffing). The number must still be easy to read when the jar is inverted (with lid on). Do not write the jar numbers on the wall or lid of the jar. On one sheet of the paper towel, write "SMELL" and on the other sheet, "NO SMELL" (Fig.3).

Lids should all be closed on the jars. Thoroughly clean up any odorant spill from the table and sides and lids of the jars. (If you are careful there will have been no spillage). Wash and dry your hands.

Shuffle the jars, into a random bunch, in front of you on the table.

The dilution series is now ready for testing.

Administering the test

Take the jars one at a time (start with any jar) and carefully open it and sniff the headspace. Do not dip your nose into the solution. Close the lid and put the jar on the sheet marked SMELL or NO SMELL according to your smell judgement of whether you could smell *anything* or not. Pause for 15 to 20 seconds before sniffing the next jar. Continue until all jars have either been judged and assigned to the SMELL group or the NO SMELL group. The test is now complete. Upon completion of the test, a result might look like this, for example:

- SMELL: Jars 1, 2, 3, 4, 5, 6, 7, **8**
- NO SMELL: Jars **9**, 10, 11, 12

Note the highest number on the bottom of the jar in the SMELL group (e.g. 8) and the lowest number in the NO SMELL group (e.g. 9).

In this example, the threshold lies between 8 and 9. Score yourself as having a detection threshold between the two: 8.5. Make a note of this result and the time and date of testing.

Interpretation of results

In this example, 8.5 is the numerical value of your smell detection threshold.

If you are becoming anosmic, this number will increase upon retest (or the liquids are losing their smell — see further detail below). In healthy people with normal olfactory acuity there should be *no change* in threshold score.

If you find you have all the bottles in the NO SMELL group, it suggests either that you didn't use an actual smell as a primary sample *or* you (already) have *anosmia*. If you think that your condition has come on recently and cannot be explained by nasal congestion or other causes, and you decide on the *anosmia* interpretation, first confirm your interpretation with the jelly-bean test (see above), then consult your health professional for a COVID-19 test.

Retesting

The jars can stand at room temperature for two or three hours.

Shuffle the jars and retest yourself after a chosen interval.

Prolonged use of the test for retesting up to 7 days: Put the jars on a small tray (e.g. a baking dish) and place them in your refrigerator (*not* in the freezer). If you wish to monitor for longer than seven days, make up a fresh set of liquids.

For retesting (say twice daily) remove the set of jars and allow to stand (lids on) for an hour to reach room temperature. Note your scores and any change between them.

If you find the scores have changed:

- A single-digit change may be inconsequential (measurement error) but a change in the direction of a *higher score* of two or more digits is indicative of a detrimental change. Retest twice after intervals of two or three hours to confirm or refute the "change" interpretation.

Conclusion

The current status of concern by medical scientists, about the role of the chemical senses in the COVID-19 pandemic, reinforces the need for authorities as well as individuals to promote and practice conscious awareness of smell and taste, in everyday life. Although the sense of smell plays an important part in our lives, we tend to ignore it. This means that we can be unaware of onset of the COVID-19 symptom, new loss of smell or taste, and crucially, our being contagious with it, until it is too late and the virus has been spread into the community. The risk of COVID-19 spreading through communities can be reduced by promoting smell awareness by everyone, using simple, inexpensive measures, suggested in this paper.

If you are losing/have lost your sense of smell as determined by change in smell threshold, consult your doctor/health service for a COVID-19 test.

If you have used this test and found yourself to be anosmic, *and* you test positive to COVID-19, or wish to communicate with the author, or share your experiences with the test and COVID-19, please post a comment to the *Ozzie Smell Test Group on Facebook*.

Disclaimer

The "Ozzie" test is free for use by all members of the global public currently concerned about their health in the time of the COVID-19 pandemic. Use of the test and interpretation of results are undertaken entirely at your own risk. No company or institution associated with the author has any claim to or responsibility for the test.

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1 See the publication for the full list of 114 authors. [Ed.]

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The magic of solo violin

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Abstract

J.S. Bach's solo violin works are widely regarded as representing one of the most sublime levels of musical thought in the entire Western canon. 2020 marks the 300th anniversary of these influential works. Interspersed with live performances of two complete works for the violin, we outline the historical reasons that the unaccompanied violin recital today is more the exception than the rule, and explore ways composers who preceded Bach influenced his music, and how Bach, in turn, influenced later composers.

Introduction[1]

If I were to hazard a guess about how many people in this room have ever attended a solo piano recital, I would be reasonably confident in saying no fewer than seventy-five per cent. If asked to make a similar guess about how many of us here tonight have ever attended a solo violin recital — and by this I mean a complete recital of unaccompanied violin, without piano — I would say no more than ten per cent.

Why is the solo violin recital today so much more the exception than the rule? The cornerstone of the solo violin repertory are the six solo violin sonatas and partitas that Bach wrote in 1720 when he was in Köthen. During this time Bach was director of music to Leopold, Prince of Anhalt-Köthen. In this period, that begins in 1717 and ends in 1723, Bach concentrated primarily on chamber music. The Brandenburg Concertos date from this time.

The six pieces for solo violin represent one of the most sublime levels of musical thought in the entire Western canon. When a violinist makes a recording of these works, it is an ordeal by fire, because he or she knows that they will be compared to the greatest violinists in the history of recorded sound. It is telling that the three premier violinists of the last century — Heifetz, Arthur Grumiaux and Nathan Milstein — all recorded these pieces.

The crucial point is that after the time of Bach, the solo violin genre went out of fashion. This continues to be a source of major regret among violinists. Imagine how much richer the world would be if there were an entire cycle of solo violin pieces courtesy of Mozart.

So when we come to the classical era, Mozart, Beethoven and Brahms all wrote for the violin, but only with accompaniment, either keyboard in the case of sonatas, or orchestra in the context of concertos. It is not until the romantic era that the genre of unaccompanied violin returns. The major figure from this period is Paganini.

The solo violin caprices of Paganini in many ways constitute the composer violinist's answer to the *Transcendental Études* of Franz Liszt. Each collection of pieces was written by a composer who was an una-

1 This talk and these performances (including the world premiere of David Hush's Violin Partita) occurred at the Sydney Mechanics' School of Arts, on 27 February 2020.

bashed virtuoso of his day, and both collections are designed to show off the technical prowess of their respective instruments. In the twentieth century, we see composers of major stature writing for unaccompanied violin. Ysaÿe, Bartók and Hindemith are cases in point.

I am pleased to report that as I speak, the solo violin genre is alive and well. Composers all over the globe are writing for it. While the number of solo violin pieces will always be eclipsed by the range of pieces written for the piano, it is heartening to observe that many composers are writing for this idiom and are showing no signs of slowing down.

It is somewhat misleading to speak of Bach's six works for solo violin as a single collection, for in reality they comprise two cycles, namely, three sonatas and three partitas. The three sonatas all adhere to the same formal design. In the first movement, while the music is strictly notated, it has the aura of an improvisation. The second movement always consists of a fugue. The third movement is slow and more relaxed than the formidable fugue that preceded it. The final movement always consists of a fast movement.

While the three sonatas all adhere to the same formal design, I do not for a minute wish to suggest they sound alike. On the contrary, it is a testament of Bach's supreme genius that, similarities in formal design notwithstanding, he contrived to invent quite different works.

The three solo violin partitas consist of a succession of dance movements. The dances on which the partitas are based come from all over Europe. For example, while the sarabande hails from Spain, the gigue is of Irish origin. No two partitas offer exactly the same succession of movement types.

While the solo violin partitas are profoundly different from the sonatas, one vital trait shared by all six pieces is the technique of implied harmony. Regardless of whether Bach asks the violinist to play a four-note chord or a single melody, he is always using the violin to project a multi-voiced texture. It is telling that on the cover page of Bach's original manuscript he appended the words *senza basso accompagnato* to the title. This is Italian for "without bass accompaniment."

In Bach's day there was a time-honoured tradition of compositions for a single melodic line and a bass or *basso continuo*. The harpsichordist would play the notated bass part with his left hand complemented by chords in the right hand. The figured bass would indicate how the chords in the right hand are voiced. A case in point is Bach's Sonata for Flute and Continuo in E minor, BWV 1034.

But with the solo violin works, Bach went out of his way to emphasise a point that was far from merely rhetorical — namely, that his compositions for unaccompanied violin were fully-fledged pieces in their own right requiring no fleshing-out of the harmony on a keyboard. In short, his solo violin works are self-sufficient: a veritable law unto themselves.

While the Viennese music theorist Heinrich Schenker has offered valuable insights into Bach's writing for solo violin, it was not until 1999 that the first book on the subject appeared: *Bach's Works for Solo Violin: Style, Structure, Performance*, by Joel Lester. As a respected theorist and accomplished violinist, Lester was ideally placed to write this book. It offers a goldmine of information about Bach's technique of implied harmony. One thing is certain. In applying this technique, Bach drew upon the solo violin compositions of his predecessors. In short, he did not invent the technique. Rather, he absorbed it and applied it with stupendous results. In a similar way, he absorbed the basic principles underlying the instrumental concertos of the Italian school epitomised by Antonio Vivaldi and drew on these principles with amazing results.

Johann Paul von Westhoff was a violinist and composer born in Dresden in 1656. He wrote six partitas for solo violin, published in 1696. It is possible that von Westhoff met Bach in Weimar in 1703. Without a doubt, there is a discernible connection between von Westhoff's writing for solo violin and Bach's. The second movement of von Westhoff's First Partita in A minor almost certainly influenced Bach in writing the first movement of his Second Partita.

The Austrian violinist and composer Johann Joseph Vilsmayr was born in 1663. He wrote six partitas for solo violin, published in 1715. The Prelude of his Fifth Partita in G minor may well have influenced Bach in writing the Chaconne of his Second Partita.

There is an important distinction between the solo violin works of Bach's predecessors and contemporaries on the one hand and those written by Bach himself on the other. The works of Bach's predecessors and contemporaries are generally played today only by baroque specialists on historical instruments, whereas the solo works of Bach have been championed by the greatest violinists of the twentieth century continuing well into this century, on modern instruments, in addition to baroque specialists.

Sometimes, Bach may use register to distinguish different voices — for example, a melody in the upper register is answered by a tune in the lower register, thus setting in motion a dialogue of voices. We will hear an example of this tonight in the third movement of Bach's First Sonata.

Music from Bach's era is renowned for the use of melodic sequences. To give an example: a violinist will play a motive. We then hear the same motive repeated at a higher pitch level. After that, the motive may be repeated a second time at a higher pitch level. The final result is the same motive moving up by step. This is known as an ascending sequence.

In Bach's solo violin works, the composer projects implied harmony by writing a single line using a sequence of ascending or descending motives. We will hear a highly developed example tonight in the final movement of the Bach composition. In that movement, we shall also hear sequences of arpeggios — a highly effective way of implying more than one voice.

There is no doubt that the use of chords contributes significantly to implied harmony.

While the violin can produce chords of up to four notes, it is not possible to attack the notes in a chord at the same time unless it is a two-note chord comprising notes on adjacent strings. The larger chords can be executed only by moving the bow across the strings.

I have already mentioned that the second movement of each of Bach's solo sonatas consists of a fugue. How is it remotely possible to write a fugue for a single stringed instrument?

Many of us have heard choral fugues written by Bach comprising free flowing polyphony at a fast tempo. A magnificent example from the Mass in B Minor is the last chorus of the Gloria, titled: *Cum sancto spiritu in gloria Dei patris* ("With the Holy Ghost in the glory of God the father.") Great genius though he was, Bach knew that he could never write for a single violin like this.

To begin with, the fugues of the solo violin sonatas each suggest a medium or medium/fast tempo, never a very fast one. Bach uses chords to punctuate, or sound against, a single melodic line. If this technique sounds simple, each specific application requires a first-rate musical mind to bring it off.

Bach's fugues for solo violin are remarkable feats of technique in their own right. They are so startling as to require many hearings in order to absorb the magnitude of his accomplishment. The word "startling" is apposite since it reflects perhaps the most admirable trait of his solo violin works — namely, that despite being precisely three hundred years old, they have aged not one iota — on the contrary, in the hands of a skilled player they sound as if they could have been written only yesterday.

Live performance: J.S. Bach Solo Violin Sonata No. 1 in G minor BWV 1001

https://www.youtube.com/playlist?list=PLYFFwCGj2FIZzj5vt2VO-rEV_69FGwqJq

Niccolo Paganini was born in Genoa in 1782. He was a virtuoso violinist of great renown. His 24 Caprices for Solo Violin were written between 1802 and 1817. They take the form of etudes, with each individual piece calling for a specific skill. Without a doubt, a formidable technique is required to play these pieces convincingly. The general consensus among musicians is that Paganini did not absorb the lesson of implied harmony from the solo violin works of Bach. Earlier on, I drew a comparison between Paganini and Liszt. As it happened, Liszt made arrangements of no fewer than five of Paganini's caprices for the piano.

Henryk Wieniawski was born in Lublin in 1835 and died in 1880. Since he was born five years before Paganini died, the two composers cannot be said to belong to the same generation. However, there is no doubt that the younger composer followed in Paganini's wake. His principal contribution to the realm of solo violin writing is a work called *L'École Moderne (The Modern School): Ten Études-Caprices*. As is the case with Paganani's caprices, each individual piece poses a formidable challenge to the violinist's skill. On listening to the whole collection I do not have a sense of a profound use of implied harmony. The main exception appears to be the sixth caprice, titled "Prelude." Here one has a definite sense of polyphony in the first section, along with the written-out reprise of that section.

Henri Vieuxtemps was born in Belgium in 1820. In being only fifteen years older than Wieniawski, he belonged to the same generation. An early work, Six Concert Etudes, Opus 16, written when the composer was twenty-five, follows in the romantic wake of Paganini. Just another composer writing in the romantic tradition? Well, not quite. A much later work, Six Morceaux or Six Pieces, Opus 55, was published posthumously. These very special pieces are much closer to the Bach tradition than to the romantic generation to which Vieuxtemps belonged. The final piece is called Introduction and Fugue, and is arguably the most transparently Bach-like, as the title may suggest.

The Belgian violinist and composer Eugène Ysaÿe was born in Liège in 1858. His principal creative legacy is a set of six wonderful sonatas for solo violin, written in 1923. Each sonata is dedicated to a different violinist whom the composer knew personally.

The solo sonatas of Ysaÿe are redolent of the Bach tradition from beginning to end. As surely as the solo pieces of Paganini are primarily monophonic, the sonatas by Ysaÿe are intrinsically polyphonic. His second sonata even goes so far as to open with a direct quotation from the Prelude of Bach's Third Partita in E Major. However, it should be stressed that in Ysaÿe's solo works, direct quotations are the exception rather than the rule.

If we were to sum up Ysaÿe's life achievement in just a few words, it might be that he succeeded in absorbing Bach into a more modern sounding harmonic idiom. On the one hand, his sonatas are traditionally tonal since they are written in a specific key. On the other hand, in certain places they reflect the influence of Debussy and the French school. For example, the third movement of Sonata No. 1 has a delightful passage consisting of perfect 4ths alternating with perfect 5ths. This would have been strictly forbidden by Bach.

When we come to the solo violin pieces of Bartók and Hindemith, it is not surprising that their sound is even more modern. While both composers are "tonal" in so far as they employ pitch centres, there is a tendency to access more notes of the chromatic scale.

While Hindemith was younger than Bartók, his works for solo violin precede Bartók's own sonata. Paul Hindemith was born in 1895 in Hanau, a small town in Germany. He died in 1963. Hindemith wrote three sonatas for solo violin. His first sonata is in G minor and was completed in 1918.

Six years later, in 1924, he wrote two sonatas that comprise his Opus 31. A mere glance at the score of his Second Sonata tells us that Hindemith had undergone a big change. To begin with, there is an absence of a key signature in each of the five movements. Moreover, while the first movement starts on the note A-natural, the final movement ends on the note A-flat. Maybe the composer was making a statement here, to the effect of: "If you are looking for a piece that begins and ends in the same key, you won't find it here!." There is no doubt that Hindemith was a learned musician who absorbed Bach's practice of implied harmony into the template of his considerably modified harmonic idiom.

Bartók wrote his Sonata for Solo Violin in North Carolina in 1944 at the behest of Yehudi Menuhin. It is his only contribution to the idiom. The Bartók sonata is steeped in the Bach tradition. To begin with, the four-movement pattern of tempos (slow, fast, slow, fast) consciously recalls the same pattern to be heard in Bach's solo sonatas. The first movement of the Bartók is marked with the tempo of a chaconne, and opens with a conscious pastiche of Bach's harmonic world. The second movement is a fugue bearing some of the characteristics of the fugues in Bach's solo sonatas. Strictly speaking, the Bartók second movement is more of a fugal fantasy than a fugue proper.

There is no doubt that the Bartók sonata is the best known of solo violin works from the last century, in part due to Menuhin's tireless championing and recording of the piece. Not all musicians, however, seem to be in agreement regarding how innate the writing is from a violinistic point of view. On the one hand, the piece is playable; on the other hand, the conductor Antal Doráti, who knew both Bartók and Menuhin personally, has called it "a fiendishly difficult work" (Yatsugafu, 2011, p. 19). Menuhin himself was convinced that the piece was almost unplayable after looking over the manuscript for the first time.

It is worth recalling that every composer referred to so far except Bartók was a violinist. While Bach is remembered primarily as an organist, he was also a highly skilled practitioner of the viola in addition to the violin.

Looking at the solo violin world today, my impression is one of unqualified diversity, with each composer doing his or her own thing, which in many respects is refreshing. An example of a very captivating piece written by a living composer is the *Cadenza for solo violin* by the Polish composer Penderecki.[2] It was written in 1984. You will find more than one live performance of the piece on YouTube.

My own Partita for Solo Violin was commissioned especially for this event tonight by the Royal Society of New South Wales. More by coincidence than by design, the piece is written in the same key as the Bach sonata: G minor. This is a wonderful key for the violin, for it draws on open strings. An open string is the name of the string which sounds when it is not stopped to produce a particular note.

While the attraction of a single-movement piece resides in its capacity to say a great deal in a short space of time, what I like about the genre of the Partita is its capacity to encompass a wide spectrum of emotions and moods.

The new piece could be regarded as a prism which refracts different aspects of East European music, with a leaning towards the Jewish. It comprises four movements. Unlike Bach's solo partitas, the work I have written does not comprise a succession of dance-movements. Instead, I have chosen the term Partita as a generic title for a multi-movement composition spanning a wide spectrum of emotions and moods.

We will now hear Anna Da Silva Chen play my piece. This will be its first performance.

Live performance: Hush Partita for Solo Violin

https://www.youtube.com/playlist?list=PLYFFwCGj2FIZ6a2tGQzJOorw7mD9JZNv0

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2 Penderecki died on 29 March 2020. [Ed.]

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The Pyrocene comes to Australia: A commentary

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Abstract

This is an invited commentary, after last summer's fires, from Stephen Pyne, doyen of those studying fires in nature around the world, and author of *Burning Bush: A Fire History of Australia* (1991); *The Still-Burning Bush*, rev. (2020); and *Fire: A Brief History, 2nd edition* (2020), revised with an Australian preface.

Australia and fire

That Australia is a fire continent is not news. Since it broke from Gondwana, Australia has increased its flammability; since the advent of humans, it has experienced an almost inextinguishable source of ignition; and since the arrival of Europeans, it has undergone a more or less continual disruption in fuels, sparks, and fire regimes that have challenged a transplanted way of living that originally emerged from a landscape not naturally disposed to burn. Australia has burned widely and routinely as far back as anyone cares to look. The first European explorers reported "fires by night and smokes by day." The record of British colonization is a chronicle of conflagrations whose names have filled up the days of the week and more, spilling across the calendar as flames have the countryside.

Yet the most recent outbreaks feel different. The bad burns seem to be coming more often, raging more savagely, and wrecking more havoc. Black Saturday and a Red Summer of forever fires might serve as geodetic markers from which to triangulate the future. Underwriting both lies another order of combustion, one that is burning lithic landscapes of fossil fuels which are interacting with the ancient fires of living landscapes. The Black Saturday fires of 2009 rampaged across a countryside shaped by coal and oil — a natural and social geography made possible by the Hazelwood Power Station and its brown coals. Of the 173 lives lost, 162 resulted from fires started from powerlines — an apt metaphor for the violence that can occur when living and lithic landscapes cross. The endless Red Summer fires of 2019/20 had a monstrous drought to ready fuels, dry lightning to kindle blazes, and a mosaic of quasi-natural fuels in protected lands and dispersed settlement vulnerable to ember storms. Climate change and land use change, both underwritten by fossil fuels, readied plentiful tinder. Against such forces — ignitions so abundant, fuels so profuse — human countermeasures were inevitably inadequate. Deluges would have to end what drought had made possible.[1]

What had been an incremental escalation in burning has made, as it were, a hydraulic jump. What have been fire fights became fire sieges. What have been outbreaks have lengthened into seasons. What have been fire crises localized in time and space are evolving into a globalized fire epoch. Call it the Pyrocene.

1 The 2020 Bushfire Royal Commission leant that March 2, 2020, was the first day for months that there were no bush fires burning. [Ed.]

The Pyrocene

When did humans begin to redraw the geography of fire on Earth? When did we go from cooking food to cooking landscapes and now to cooking the planet? Every observer will have his or her preferred marker.

My reading is that it took the sudden warming of the interglacial to create ideal conditions for a fire-wielding species to propagate its most potent technology. Humans and fire forged an alliance in which each would expand the range and power of the other. Together, they could interrupt the cycle of frost and thaw that had characterized the Pleistocene. They could nudge, and then shove even climate.

By burning, Aboriginal economies could prevent woods from reclaiming the wetter grasslands — the tropical savannas, the sourveldt, the tallgrass prairie, the pine steppes, the cerrado and llano. With fire as a catalyst, agricultural economies could actively clear and convert, or slash and burn through peat and moor as well as forests, adding methane from irrigation and livestock. When burning stopped in the grasslands, many filled with woods or thickened their presence. When people abandoned fields from disease, famine, or war, the forests returned.

All this occurred within broad ecological baffles and barriers. What burned was living landscape, and there were limits on how much and how frequently fire could return, or what else could interact with fire. The land could be exhausted, unable to recover quickly, its fires starved along with other inhabitants.

That changed when people, ever eager for more fire power, turned to lithic landscapes. Revealingly, the earliest steam engines were used to drain coal mines to make more fuel available. These combustibles have proved essentially unbounded and so have their byproducts, which are no longer constrained by the primordial rhythms that governed fire over the past 400 million years. They can burn day and night, winter and summer, through wet and dry, year after year. There is no sink adequate to the source. Instead, the effluent overloads the atmosphere, the biosphere, the hydrosphere, the Earth. We are taking stuff from the geologic past, burning it with unanticipated consequences in the present, and releasing its residue into the geologic future.

Similarly, there seems no inherent limit on the power humanity derives from such combustion until, at some point, the planet becomes uninhabitable for people. Most observers have focused on the impact of emissions on climate change. But burning's byproducts also affect how people organize and live on landscapes. They affect transport, which also determines how natural resources and agriculture connect to markets, and how people choose to arrange their residences. And they actively seek to replace open fire, from candles to field fires, with fossil-fuel-powered surrogates, and, where substitution fails, to suppress any expression of flame.

In setting after setting, this pyric transition — the shift from burning living to burning lithic fuels — has remade where and how people live. Satellite images of the Earth at night show the divide clearly. Sub-Sahara Africa glistens with flames burning through living landscapes. Europe glows with electricity powered by fossil-fuel combustion, or with technologies for which such combustion is a catalyst. Save for a period of transition, only one kind of fire or the other exists at any site. Industrial combustion doesn't play well with others.

Working fires are mostly gone from modern cities and residences; are going from agricultural practice; and are disappearing from protected nature reserves. In industrialized countries the rural landscape is being recolonized by an urban out-migration and a service economy, which also eliminates the buffer zone of fields and paddocks around rural towns and the routine burning that dampened wild fires. In many settings the crisis is not a surplus of uncontrollable fires but a deficit of controlled ones. Like the demographic transition with human populations, the pyric transition leaves the population of fire below ecological replacement value.

Thanks to transport and climate change, local impacts have generalized — have, in fact, globalized. The contours of the fire equivalent of an ice age are taking shape with megafires, fire-informed biotas, melting ice packs and permafrost, spreading deserts, and mega-smoke palls taking the place of ice sheets, mountain glaciers, a frozen Arctic, thickening permafrost, pluvial lakes, and outwash plains. Fire creates the conditions for more fire, as ice did for ice. Climate is warming. Sea level is rising. Mass extinction is underway.

The Age of Humans, the Anthropocene — there are many terms to describe the plexus of fluxes. Pyrocene gives us a continuous narrative that dates back to that ancient alliance between humanity and fire and it grants a vivid analogue around which to cluster the bewildering swarm of changes. The upshot is too much bad fire, too little good, and too much combustion overall. It adds up to a fire age.

The Pyrocene in Australia

Australian history intersects this most recent phase change in curious ways. Its contact with Europe tracks, with eerie fidelity, the acceleration in humanity's firepower that has made the Pyrocene not simply a check on a succession of glacial breakouts but a runaway phenomenon in its own right.

Three events converged. Geopolitically, Captain James Cook explored eastern Australia in 1770; Joseph Banks proposed a penal settlement in 1779; the First Fleet arrived in January, 1788. Technologically, James Watt invented the first successful steam engine between 1765 and 1776 and effectively announced the prime mover behind the industrial revolution. And, intellectually, Joseph Priestly announced the discovery of "dephlogistinated air" which Antoine Lavoisier confirmed and more memorably named oxygen in 1774 and 1777, respectively. As an autonomous phenomenon, fire lost its standing; as an integrative concept, fire shed its capacity as an organizing principle for explaining what was happening. It disappeared from scientific consciousness at the same time it began vanishing into machines. Out of sight, out of mind.

Enlightenment science birthed a new wave of pyrotechnologies. Its reductionism was ideal for deconstructing processes into their elemental parts and then building tools to express them separately. It was now possible to have heat without flame, light without heat, combustion without plumes of smoke. This new power fed long-standing suspicions among European elites regarding fire. They distrusted free-burning flame, hated fallowing (needed to furnish fuel for agricultural fires), and stigmatized the use of fire as inherently primitive; to be rational and modern demanded an alternative to open fire. These attitudes were applied not only to native peoples in colonies, but to peasants in Europe itself. But it also left fire practitioners without a science to guide them.

In brief, the steam engine added a novel pyrotechnology that had the power to unmoor the ancient alliance between humanity and fire; European imperialism provided a vector by which to propagate European settlers, institutions, and ideas around the world; and the redefinition of fire through Enlightenment science helped make the resulting changes — the entire narrative of landscape fire — increasingly invisible except as spasms of disaster. That a continent so fire-rich as Australia should feel the consequences early and often is not a surprise. That its human history should so eerily align with its natural history does.

Of course, anthropogenic fire did not begin with émigré Britons. Aboriginal fire practices had already altered Australia's biota over the course of tens of millennia — how much remains a matter of dispute. In Australia anthropogenic fire found an especially receptive environment. It affected landscapes at a large scale long before it influenced Europe, North and South America, and most of Eurasia. We might consider the experience a dress rehearsal for that greater reformation prompted by the arrival of industrial combustion, which, thanks to Britain, Australia felt early and offered an inviting environment.

What I find more interesting, however, is the way that legacy of anthropogenic burning persists. The Aboriginal firestick keeps reincarnating. After the shock of contact, the "firestick habit" was picked up by rural Australians. After World War II foresters adopted it as a principle of land management, one they celebrated as having grown out of Australian experience and that contrasted both with British examples, which sought to ban fire, and with American ones, which sought to rally paramilitary muscle to suppress it. Australia's foresters were the only group of foresters to embrace deliberate burning; it's not hard to believe that the stubborn persistence of the firestick is a reason. Then ecologists countered with a firestick of their own, shifting the focus from hazard reduction to biological values. Now Indigenous peoples are rallying around a revival of traditional burning as a means of restoring heritage as well as country.

Each group has its own term, context, and purpose for the practice, and the whole discourse has come to pivot around something like identity politics. The Aboriginal firestick farming made famous by Rhys Jones (1969) evolved into the "burning off" of rural Australia, then into "firestick forestry," "firestick ecology," and "cultural burning." Controversies over how and where to deliberately burn is a staple of Australian fire politics. At least three royal commissions (1939, 1961, 2010)[2] have granted it a central role. With cause: in a fire-prone place, the choice is not whether the land will burn but when and with what effects. The firestick is a device that can transmute bad fire into good, and in social settings it can be a symbol, lever, or club. Over and over, it becomes synecdoche for the whole, tangled issue of how Australians live on a fire continent.

There are practical concerns, too. Among many paradoxes, as we ratchet down our binge-burning of fossil fuels, we'll have ratchet up our routine burning of living

2 Stretton (1939), Rodger (1961), Teague B. et al. (2010).

landscapes. A fossil-fuel civilization has already baked into the future a new climate and patterns of economy and society. Even if fossil-fuels were abolished tomorrow, the lag times would leave us with hazards and risks for many decades. We will have a lot more fire — will, again paradoxically, need a lot more fire. What kinds of fires Australia will have is a legitimately political question. Science can advise how to do better what people choose to do and what the likely consequences are of various choices, but it cannot choose. That is a deeply cultural matter. For the sapients it is among the earliest choice the species made. Whether as mutual assistance pact or Faustian bargain, it put us on a path we have never left.

Among the dramatic changes in recent times is an exponential increase in fire science. Fire still has no disciplinary home; the only fire department on a university campus is the one that sends emergency vehicles when an alarm sounds. But landscape fire is no longer the exclusive bailiwick of forestry. Geographers, ecologists, climatologists, physicists, chemists, mechanical engineers, meteorologists, even social scientists and lawyers, even historians, novelists, and poets are publishing on fire as viewed through the prism of their home disciplines and genres. As it has in natural landscapes, fire has once again diffused through intellectual culture.

The Pyrocene: Australia can choose

Australia is feeling the harsh shockwave of an advancing Pyrocene. It feels it early because it has long been a fire continent, and because the pressures of the Pyrocene act like a performance enhancer. They make fire-prone places more fire-driven. They make fire-spared places more fire-susceptible.

Unlike many regions, however, Australia is better positioned to respond. It has fire institutions, long experienced in lighting and fighting bushfires. It has a robust suite of fire sciences — has made fundamental advances in fire behavior, fire ecology, and fire anthropology. It has an unbroken tradition of fire art that traces back to Aboriginal bark paintings. It has a fire literature of novels, poems, and histories. It has a politics that recognizes that bushfires are a persistent problem. Its fire history harks back to an Indigenous heritage of firesticks and to a Britain that, more than any other country, outfitted a mild Pyrocene with steam, then transported it around the globe, and bequeathed a full-blown Pyrocene. It has a population that, for all their laments about the strangeness of an urban, British-founded society on a sunburnt continent, and for all the ineluctable alienness of bushfire, is accustomed to fire on the land. Modern Australians still record a chronicle of smokes by day and fires by night.

First to experience, first to lead — Australia can turn what promises to be a problem Pyrocene into an opportunity; only the U.S. has a comparable technological and cultural capacity. Europe outside the Mediterranean, for example, has almost none of Australia's experience and fire culture to tap into. Other continents have fire and folklore but lack institutional heft. In a planet increasingly informed by fire in all its manifestations, a world that is segueing into the fire equivalent of an ice age, its experience counts. Australia is a firepower. How it uses that power matters to the rest of us.

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Making SPACE for Australia: Convenors' report

The Royal Society of New South Wales and Four Academies Forum, Government House 7th November 2019

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This year's Royal Society of NSW and Four Academies Forum devoted to the subject of "Making Space for Australia," drew together, in one day, authoritative voices from the natural, technological and social sciences and the humanities, to consider a range of issues that are likely to inform Australian public policy and public opinion in the decades ahead.[1]

Held like the four previous Forums, under the gracious Vice Regal patronage of the Governor of New South Wales and in the ballroom of Government House, Sydney, the inclusive gathering of 140 people represented the Royal Society of NSW, the four Learned Academies, and guests from a cross-section of the space community, including 13 undergraduate students from diverse faculties across six universities and studying various aspects of space.

Her Excellency the Honourable Margaret Beazley, AO, QC, Governor of NSW, reflected during her opening remarks on Australia's long interest in reading the Heavens, beginning with the earliest Aboriginal observations and understanding of the constellations and their configurations.

Introduced by Professor Anne Green, Chair of the NSW Division of ATSE, the Keynote speaker, Professor Lisa Kewley, emphasized Australia's strengths in space science while taking us on a tour of the Universe. The next session, Australia in the Space Age, moderated by Professor Jane Hall, President of the Academy of the Social Sciences, heard papers by the space historian and curator, Kerrie Dougherty on "Sixty years of Australia in space," by Dr Megan Clark (Director of the Australian Space Agency), on the Agency and its work; by Dr Kimberley Clayfield, on CSIRO's "Roadmap for space;" and by Dr Adam Lewis, of Geoscience Australia, on "Seeing and sensing Australia from space."

Dr Donna Lawler, Principal of Azimuth Advisory, moderated the session devoted to Space Law, Security and Ethics. Prof Steven Freeland, the distinguished international Space lawyer, summarized the "Limits of law" in Space, and Dr Ben Piggott of UNSW Canberra reminded us of the military and geopolitical dimensions of Space policy. Dr Nikki Coleman, RAAF chaplain and Space

1 This Report appears on-line, at the Royal Society web site, https://royalsoc.org.au/council-members-section/459-making-space-for-australia-royal-society-of-nsw-and-four-academies-forum-2019 which also contains links to the Society's YouTube channel, https://www.youtube.com/channel/UCoyHmDj2VLkgnpm-t7sIzSQ/, which contains links to videos of the presentations at the Forum.

ethicist, explored the "Ethical challenges in space: norms and conventions in peaceful spacefaring."

A third session, expertly conducted by Ms Annie Handmer, historian of science of Sydney University, on Space and People, highlighted key themes in what is fast becoming the "humanities of space," with papers by Jonathan Webb, of the ABC, on "The promise and peril of space;" by Dr Alice Gorman, of Flinders University, on "Space heritage: artefacts and archæology" (both now challenged by the profusion of space debris); a theme capped by the writer and novelist Ceridwen Dovey, on "The privatisation of space."

The final session, Australia's Space Economy, moderated by Dr Susan Pond, AM, Chair of the NSW Smart Sensing Network, brought us back to Earth, welcoming William Barrett, Senior V.P. of Asia Pacific Space consultants, who addressed Australia's promising space industry, then Paul Scully-Power, AM, one of Australia's pioneering astronauts, speaking about the challenge presented by "Space 2.0: Small Smart Satellites." Finally, Group Captain Jason Lind explained the role that Defence must and is playing in supporting Australia's Space industry.

Our rapporteur, Dr Brett Biddington, AM, of Canberra, skillfully summarized the day. He reminded the audience that by a unique combination of history, science, and geography, Australia occupies an important place on the front line of continuing discoveries in space. He noted the tension between the civil and the defence realms in space as well as an even bigger tension emerging between public and private investment in space.

Judging from the RSNSW's customary post-conference survey, the Forum met the challenges of the day, inciting a wide range of questions that continued long after the proceedings ended. At the same time, it foreshadowed a number of fresh questions that may well be asked by academics, governments, and the public at large and at future RSNSW events.

To paraphrase C.P. Snow, Australia has the future in its sights, and SPACE holds great prospects for the next generation. Bearing a distinguished 50-year history of space engagement and blessed with major space-related facilities across the country, Australia can play a far-reaching role in the coming years, not only in science and technology but also in law and ethics.

In our view, these papers collectively define Australia's strengths, set directions, outline and present roadmaps, and create new roles and opportunities for our universities, government and industry. At the same time, they raise questions that should guide policy across issues ranging from domestic, agricultural and environmental surveillance to the codification of rules and convention for international cooperation in the control of space debris and corporate competition. These questions were drawn out by Dr. Len Fisher, FRSN, on the ABC Science Show (14 March 2020), calling urgent attention to the "tragedy of the commons" — the potential competitive overuse of communal resources — that is now playing out in Space. In this and other domains — whether in advancing precepts for regulatory law, or in proposing and defending normative standards of accountability — Australia stands at a turning point in its history, and in the history of Australia's contribution to human endeavour in Space.

What role Australia will now play in this story, the rest of the world will carefully watch and record. We have been reminded, in celebrating the 50th year since Apollo 11, that the American astronauts left a plaque on the Moon that recorded the belief that "We came in peace for all Mankind." The adventure that lies before us — as set out in this pioneering issue of the *Journal & Proceedings of the Royal Society of NSW* — is one in which Australia accepts both this challenge and its responsibilities. We can only hope this sentiment guides our leaders, in pursuit of our collective destiny, and remains our uppermost goal.

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Making SPACE for Australia

Her Excellency the Honourable Margaret Beazley AC QC

Governor of New South Wales
Patron of the Royal Society of New South Wales

Abstract

This is the opening address given by Her Excellency the Honourable Margaret Beazley AC QC, Governor of New South Wales, Patron of the Royal Society of New South Wales, to the *Royal Society of New South Wales and Four Academies Forum on Making SPACE for Australia*, at Government House, on Thursday, 7th November, 2019.

Good morning, esteemed Fellows and Friends, I, too, pay my respects to our traditional owners and custodians of this land, the Gadigal of the Eora Nation, and Aboriginal and Torres Strait Islander Elders, past, present and emerging. As we know, and as Professor Sloan has pointed out through his explication of the significance of the Australian Space Agency logo, Australia's Indigenous peoples have long had a connection with space, stretching back some 65,000 years. They were, indeed, this land's first skytrackers, cosmologists and astronomers.

For Indigenous peoples, the stars provided a calendar, a map and a navigational tool; from the stars they also read the tides and the weather.

The Milky Way determined many Indigenous seasonal activities, including uses of land and the search for food. Just one example of this explains to us how the stars were used by Aboriginal people in their daily life, in particular, to find food.

I recently listened to the TED Talk of a young Wiradjuri woman, Kirsten Banks.[1]

An astrophysicist and guide at the Sydney Observatory, Kirsten spoke about how the stars provided a "seasonal menu" for Aboriginal people. She gave the example of how the constellation, *Gugurmin*, in Wiradjuri language, the Emu constellation, guided the Wiradjuri people to find a rich source of nutrition — emu eggs.

At different times of the year, the Emu constellation would appear in different positions — sometimes running, sometimes sitting. When the Emu was in the sky directly overhead following sunset, and looked like an Emu atop a nest, Aboriginal people knew that it was the right time to go looking for emu eggs. An Aboriginal tool, called an Emu Caller, which looked like a short didgeridoo, would be used to "call" the Emu from the nest by imitating the sound of another Emu, providing the perfect decoy and lure to enable the eggs to be collected.

This connection between the stars, Aboriginal culture and land use, involved in these reflections of age-old Indigenous astronomy, is a science deserving of a conference of its own, perhaps on a relevant anniversary celebrating the work of David Unaipon, astronomer, scientist and Ngarrindjeri Elder (1872–1967).

1 https://tedxsydney.com/talk/65000-yrs-the-great-history-of-australian-aboriginal-astronomy-kirsten-banks/

The past year has been a year of space anniversaries and significant milestones:

- 12 December 2018 — the Prime Minister announced the plan to open the Commonwealth's new Australian Space Agency in Adelaide, providing a launching pad to triple Australia's space economy to $12 billion and create up to 20,000 jobs by 2030.[2] In NSW, planning continues for the Western Sydney Aerotropolis, a transformational economic hub for the aerospace as well as other industries.[3]
- 20 July 2019 saw the celebration of the 50th anniversary of NASA's Apollo 11 lunar mission and the historic and momentous occasion of the landing on the Moon.
- 22 September 2019 — The Australian Space Agency and NASA announced the launch of a new partnership[4] on future space cooperation. This opportunity for Australia to join the United States' Moon to Mars exploration, including NASA's Artemis lunar program,[5] is of singular national importance, strategically, in terms of scientific research and application and job creation.
- On 1 October this year, the University of Adelaide announced the set up of a Space Exploration Centre, to consider uses of space in terms of water, minerals, resources and habitation.[6]
- In amongst this mix of events, the Chinese have landed rovers on the far side of the Moon[7] and declared ambitions with Russia to team up to further their space station plans.[8] India's Space Research Organisation is planning to have a space station orbiting by 2030.[9] Fifteen nations are members of the International Space Station program.[10] In the blink of an eye, it seems, there is a new development in space.
- And by 2030, the US plans to arrive on Mars with the first crewed Mars landing,[11] presumably cracking the code on *why it is that "men come from Mars"* …

These breathtaking global plans raise a number of questions:

- The global space economy was worth an estimated $345bn in 2016.[12] How strongly should Australia participate in what

2 https://www.pm.gov.au/media/australian-space-agency-adelaide

3 https://www.planning.nsw.gov.au/Plans-for-your-area/Priority-Growth-Areas-and-Precincts/Western-Sydney-Aerotropolis

4 $150 million deal

5 https://www.industry.gov.au/news-media/australian-space-agency-news/australia-to-support-nasas-plan-to-return-to-the-moon-and-on-to-mars

6 1 October 2019 Media Release: https://www.adelaide.edu.au/enterprise/UoASpaceExplorationNews

7 Robotic lunar probe Chang-e-4 landed on 3 January 2019, following a record 39 orbital launches, more than any other nation. https://signal.supchina.com/chinas-space-program-is-taking-off/

8 https://www.space.com/russia-china-moon-exploration-partnership.html

9 https://www.firstpost.com/tech/science/space-week-2019-india-plans-to-have-an-orbiting-space-station-by-2030-heres-what-we-can-expect-6825141.html

10 The ISS consists of Canada, Japan, the Russian Federation, The United States, and eleven Member States of the European Space Agency (Belgium, Denmark, France, Germany, Italy, The Netherlands,Norway, Spain, Sweden, Switzerland and The United Kingdom).

11 https://www.space.com/nasa-mars-landing-apollo-11-50th-anniversary.html

12 https://www.gigabitmagazine.com/telecoms/space-law-why-extra-terrestrial-economy-needs-regulating

may easily become another — trillion dollar — "space race"?

- What is our role nationally and internationally in regard to space security, space ethics and space law? We have a number of international agreements (many signed in the 1960s and '70s) and we have recently updated our own legislation, the *Space Activities Act 1998* to become the *Space (Launches and Returns) Act 2018*.[13]
- How do we govern our activities in space, both now and in the future? Who will take responsibility for space debris, for example?
- How closely do we want to align with societies such as the Mars Society?
- In the increasing militarization and commercialisation of space, are we setting ourselves up for a new era of colonial conflict? Already we have a new space vocabulary — "space mining," "space economy," "space weapons" and "space army."
- What are our humanitarian considerations — and our responsibilities to our own planet — in pushing for research and development of this frontier, which is, as Antarctica was, ripe for exploitation?

Is the choice, as H.G. Wells once posed: "All the universe … or nothing"?[14]

Or are there positions between these two polarities?

In discussing, debating and driving our conversations forward to the stars and — just as importantly — bringing them back to Earth, I thank the Royal Society, our four Learned Academies and our esteemed moderators and presenters, for the preparation of your illuminating and insightful presentations. I am sure they will be well-received … *universally*(!)

It is my honour to now open this fifth Royal Society of New South Wales and Four Academies Forum: "*Making SPACE for Australia*."

Acknowledgements

I thank Professor Ian Sloan AO FAA FRSN — President of The Royal Society of NSW — for his Welcome and Acknowledgement of Country. I acknowledge the Royal Society of NSW Vice Presidents and Councillors, representatives from the four academies: — the NSW Academy of Technological Sciences and Engineering, the Australian Academy of Science, the Australian Academy of the Humanities, and the Academy of the Social Sciences in Australia — representatives of the NSW Office of Chief Scientist and Engineer and the NSW Smart Sensing Network, the 2019 Annual Forum Planning Committee, and finally Distinguished Fellows, Distinguished Guests, Ladies and Gentlemen.

13 https://www.legislation.gov.au/Series/C2004A00391

14 HG Wells, *Things to Come* (1936)

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Australia's strengths in space science

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Abstract

Australia has a long history of space science discoveries. Recent Australian discoveries include the discovery of the most pristine star known, the most distant spiral galaxy, and a massive explosion from the black hole in our own Milky Way, 3.5 billion years ago. These discoveries provide crucial tests of star formation theory, galaxy evolution modelling, and models of the gas around supermassive black holes. Australian astronomers are also extensively involved in the development of new astronomical instrumentation for space, including the Skyhopper satellite, and laser-guided space debris tracking and de-orbiting systems. Finally, Australian astronomers are poised to take advantage of the upcoming James Webb Space Telescope, due to be launched in 2021.

Introduction

Space telescopes are critical to Australian astronomy. Astronomers require space telescopes for multiple key reasons. Our atmosphere absorbs and scatters light at ultraviolet wavelengths, rendering ultraviolet astronomy almost impossible from the ground. Ultraviolet astronomy is necessary for understanding star formation in galaxies, and for modelling the full spectral energy distribution from individual stars and from entire stellar populations.

Our Earth and our atmosphere emit significant amounts of infrared radiation, making infrared astronomy of faint sources extremely difficult. The light from distant galaxies is redshifted, such that the rest-frame optical or UV light is shifted into the infrared spectrum, and is only visible from space.

Finally, our atmosphere blurs and distorts images of astronomical objects. This effect, called "seeing," is seen most often on low-altitude sites where the ground layer or higher layers in the atmosphere experience substantial turbulence. The best sites in the world for astronomy are at high altitude (2500–4000 m above sea level), enabling the telescopes to operate above the typical local cloud inversion layer. Even at these altitudes, seeing affects these observations.

Astronomical instrumentation laboratories around the world, including the Advanced Instrumentation and Technology Centre at the ANU, have developed laser-guided adaptive optics to help overcome these limitations. Space avoids seeing entirely, and offers the best solution for targets where high-precision images are required.

Space telescopes are now operating at all wavelengths, from the gamma-rays and X-rays, through to the UV, optical, infrared, sub-mm, and microwave wavelengths.

In this paper, I outline some of the fundamental areas where Australia is producing leading research using space telescopes. I also briefly discuss the recent Australian astronomy developments in cube satellites.

Chemical evolution of the elements

One of the key goals of the Australian Research Council Centre of Excellence for All-Sky Astrophysics in 3-Dimensions (ASTRO 3D) is to understand the chemical evolution of the elements from the first stars in the universe to the evolution of the chemical elements in our own Milky Way. Within ASTRO 3D, Australian astronomers are combining the GAIA satellite with ground-based data from the Skymapper telescope and the world's largest 8–10 m telescopes to search for the first stars in the universe. Some of these first stars are likely to exist in our own Milky Way, and are identified by their spectra containing the least amount of chemical elements known. ANU astronomers have discovered the top three most pristine stars in the universe (Nordlander et al. 2019).[1]

The first galaxies in the universe are being searched for by University of Melbourne researchers with the Hubble Space Telescope (e.g., Livermore et al. 2018). This team are analysing galaxies that are at redshifts of z~8, looking back 13 billion years ago, when the infant universe was only 5% of its current age.

Researchers at the ANU and the University of Sydney are tracking back the chemical history of the Milky Way. This field, called Galactic Archeology, uses the Milky Way's fossil record of stars. The Galactic Archeology (GALAH) team combines data from the GAIA satellite with high-resolution spectroscopy from the world-leading HERMES instrument on the Anglo-Australian Telescope. This combination of space- and ground-based data allows astronomers to measure the ages and chemical abundances of hundreds of thousands of stars in the Milky Way. So far, this team has measured ages and chemical abundances of 500,000 stars in the Milky Way. Theoretical models predict that when we reach 1,000,000 stars, we will be able to track back the chemical and accretion history of the Milky Way to its formation.

Exciting discoveries have been made along the way. The GALAH used the Hubble Space Telescope to show that a massive flare was produced by the supermassive black hole in the centre of our galaxy 3.5 million years ago. The impact of this massive explosion was felt 200,000 light years away (Bland-Hawthorn et al. 2019).

Galaxy evolution

Australian astronomers use space telescopes to understand the formation and evolution of galaxies across cosmic time. To observe the most distant galaxies, Australian astronomers use gravitational lensing. Predicted by Einstein, a large mass in the universe (such as a cluster of galaxies) bends light around it, mimicking the light path through a refracting telescope that has a diameter many galaxies across). The combination of space telescopes, gravitational lensing, and 8–10 m class telescopes have led Australian astronomers to make major discoveries in galaxy evolution, including the discovery of the most distant spiral galaxy (Yuan et al. 2017). This discovery provides a major test of galaxy formation and evolution models, which have predicted a later formation of spiral arms.

1 See this and the other references for figures, diagrams, and images. [Ed.]

Australian space instrumentation development and testing

Recently, Australian astronomers have been involved in the development of CubeSats for space astronomy. A CubeSat is a miniature satellite that is made of 10 cm × 10 cm × 10 cm units. The weight limit of CubeSats is stringent; it must be less than 1.33 kg per unit. Multiple CubeSats can be launched into orbit simultaneously, and launch is relatively inexpensive.

ANU astronomer Brad Tucker is developing a completely different space astronomy mission. GLUV is a program to place telescopes onto Google's balloons (called Google Loon). The Google Loon program aims to launch balloons over rural regions around the world to improve world-wide internet connectivity. While Google Loon is looking down at earth, GLUV telescopes are looking up into space to understand core collapse supernovae. Core-collapse supernovae are massive explosions produced by giant stars when they complete their fusion processes in their core. The outer layers are blown off in supernovae, with the core collapsing into a neutron star or a black hole.

University of Melbourne astronomer Michele Trenti is leading an international team to build a CubeSat called Skyhopper. Skyhopper is a 22 kg satellite with an infrared camera with rapid response capabilities. The infrared detector needs to be cooled to –130 degrees C to reduce detector noise and obtain high sensitivity to astronomical objects. The detector is currently being built and will be used to search for extrasolar planets, as well as to look for the first stars and galaxies.

The Advanced Instrumentation and Technology Centre at the ANU houses the largest space satellite testing facility in the southern hemisphere. This facility includes thermal and vacuum test facilities, vibration and shock testing facilities, and an anechoic chamber to test communications systems for space.

ANU InSpace and EOS Space Systems are developing a world-class laser space debris tracking and de-orbiting system. They have developed a photon pressure laser that is capable of nudging space debris to de-orbit them. They will first use low-powered lasers to detect and follow space satellites and identify debris to be de-orbited.

InSpace is also developing the first space laser communications system, touted as being an "un-hackable" system. Laser communications systems have many applications, including quantum encryption, distributed quantum computing, synchronising atomic clocks, and long-baseline quantum sensing.

The future

Astronomers in Australia and around the world are looking forward to the upcoming launch of the James Webb Space Telescope. Due to launch in 2021, the James Webb Telescope is an all-infrared telescope, designed to detect the first galaxies in the universe, and to reveal Earth-like planets around other stars. Australian astronomers are part of world-wide teams that will receive the first data from the James Webb Space Telescope, called the Early Release Science Program. Stay tuned!

Acknowledgements

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Sixty years of Australia in space

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Abstract

Australia's involvement in space activities commenced in 1957, at the beginning of the Space Age, with space tracking and sounding rocket launches at Woomera. By 1960, Australia was considered one of the leading space-active nations and in 1967 became one of the earliest countries to launch its own satellite. Yet by 1980, Australia's space prominence had dwindled, with the country lacking both a national space agency and a coherent national space policy. Despite attempts in the latter part of the 1980s to develop an Australian space industry, the lack of a coherent and consistent national space policy and an effective co-ordinating body, left Australia constantly "punching below its weight" in global space activities until the Twenty First Century. This paper will briefly examine the often-contradictory history of Australian space activities from 1957 to the announcement of the Australian Space Agency in 2017, providing background and context for the later papers in this issue.

Introduction

For 60,000 years the Indigenous people of Australia have looked to the sky, using the stars to determine their location, find their way across the land and mark the passage of the seasons and the best times to undertake specific activities. Today we would refer to this as using space for 'position, navigation and timing'.

Sixty years ago, a new generation of Australians also looked to the sky: for both military and scientific reasons, they wanted to explore space to better understand the cosmic environment in which the Earth itself exists.

What we now refer to as the Space Age, commenced in 1957, when the Soviet Union launched the world's first satellite, Sputnik-1. This paper presents a brief overview (a 'speed dating' version, if you will) of the history of Australian space activities over the past 60 years, which will provide some context for the later papers in this issue.

Launchpad: the Woomera Rocket Range

> "*If the Woomera Range did not already exist, the proposal that Australia should engage in a program of civil space research would be unrealistic*". (NAA: A1945, 227/1/39)

This 1959 quote from the Australian Academy of Science highlights the crucial role played by the Woomera Rocket Range in the inception of space activities in Australia, although the establishment of the Range itself was unrelated to space research. Woomera was founded in 1947 as a weapons development and testing facility, primarily for the United Kingdom's long-range missile program (Morton, 1989). However, managed by the Australian Defence Scientific Service (ADSS),[1] Woomera's vast downrange areas and the specialised skills in missile technology, launch and precision tracking that had

1 The ADSS was the predecessor of the today's Defence Science and Technology Group.

been developed to support the weapons testing programs there, meant that the Rocket Range was ideally placed to become the hub of early space activities in Australia.

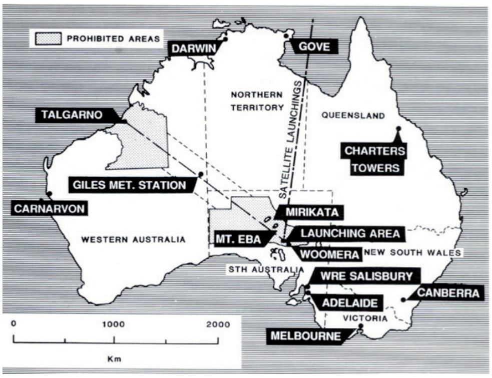

Figure 1: Location of the Woomera Rocket Range showing the extent of its downrange areas and satellite launching corridor.

The International Geophysical Year

The catalyst for Australian involvement in space activities was the IGY, or International Geophysical Year, a period of 18 months between July 1957 and December 1958 dedicated to a global scientific research program that focussed on the relationship of the Earth to its broader space environment (Doyle, 2012).

In 1955, both the United States and the Soviet Union, announced that they would attempt to launch a satellite during the IGY. Australia, and particularly the Woomera Range, were in the right place geographically and geopolitically to host tracking and data reception stations for the two networks that the United States wanted to construct around the world for its satellite program: the Minitrack radio interferometry tracking and data reception system; and the Baker-Nunn telescope tracking cameras (Tsaio, 2008). A Minitrack station was established at Woomera in 1957, followed by a Baker-Nunn camera observatory in 1958. These two facilities marked the beginning of Australia's long-term involvement in space tracking.

Space tracking in Australia

When NASA was formed in 1958, the two IGY tracking stations were transferred to the new agency. By 1969, Australia was playing host to the largest number of NASA tracking facilities outside the United States, supporting each of its three networks: The Deep Space Network, for robotic lunar and planetary exploration; the Manned Space Flight Network and the Space Tracking and Data Acquisition Network, for orbiting scientific satellites (Mudgway, 2002; Tsaio, 2008). Although funded by NASA, these stations were staffed and operated by local personnel, enabling direct Australian participation in the Unites States' space program.

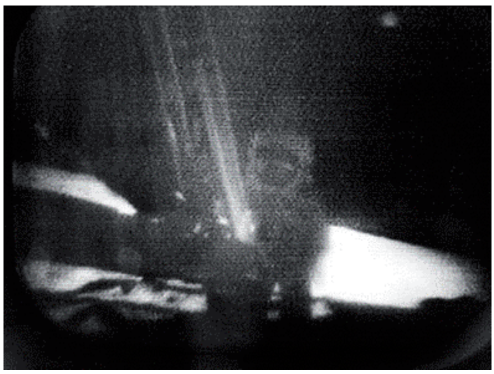

Figure 2: Armstrong stepping onto the lunar surface, as seen around the world via the Honeysuckle Creek tracking station.

The most significant space tracking event with which Australia has been involved to date was the reception of the television images of the first human mission to the lunar surface, Apollo 11. Commander Neil Armstrong's first step onto the lunar surface was received at NASA's Honeysuckle Creek tracking station, near Canberra, while the majority of the Apollo 11 lunar television was broadcast to the world via the CSIRO Parkes Radio Telescope (Lindsay, 2001; Dougherty and Sarkissian, 2010).

One of the world's great astronomy instruments, the Parkes Radio Telescope has had a long association with NASA, assisting with its various space tracking programs. In the 1960s, its innovative design served as the prototype for the 64 metre antennae of NASA's own Deep Space Network (Sarkissian, 2001).

Today Australian involvement in space tracking programs and the exploration of the solar system continues. On behalf of NASA, CSIRO manages the Canberra Deep Space Communications Centre in the ACT. CSIRO also manages the European Space Agency's space tracking complex at New Norcia in Western Australia.

Sounding rocket programs at Woomera

Military and civilian interest in the nature of the Earth's upper atmosphere converged during the IGY, encouraging the development of sounding rockets, sub-orbital launch vehicles capable of carrying scientific instrument packages to the fringes of space, although not into orbit. Britain and Australia were among a handful of nations that developed sounding rockets during the IGY (Berkner, 1958; Doyle, 2012), both programs intended to support the missile research projects at Woomera as well as IGY scientific research. Several hundred British, Australian, European and American sounding rockets were launched from Woomera between 1957 and 1979 when the last of the sounding rocket programs ended (Dougherty, 2006).

The most significant sounding rocket program at Woomera, and the longest-lasting, was the British Skylark, first launched in 1957. Although Skylark's origins lay in defence research, it transitioned across the 1960s into a versatile tool for space astronomy (Brand, 2014). Among the research institutes to use Skylark were the Universities of Adelaide and Tasmania, which conducted ultra-violet and X-ray astronomy research that led to important discoveries in X-ray astronomy (McCracken, 2008).

The Weapons Research Establishment (WRE), the division of the ADSS directly responsible for the Woomera Range, developed Australia's first sounding rocket, the High-Altitude Research Program (HARP) in 1956. Although unsuccessful, the HARP rocket demonstrated Australian innovation with the earliest-known use of glass fibre reinforced plastic (fibreglass) in the space sector (Ordway and Wakeford, 1960; Dougherty, 2017).

HARP's more-successful successor, the Long Tom, paved the way for an extensive program of Australian upper atmosphere research, much of it conducted in conjunction with the University of Adelaide. The early WRE sounding rockets were Australian designed but composed of surplus British rocket motors. Across the 1960s, the Australian-made content of the WRE sounding rockets increased, with the first 'all-Australian' vehicle, Kookaburra, becoming operational in 1968 (Dougherty, 2006).

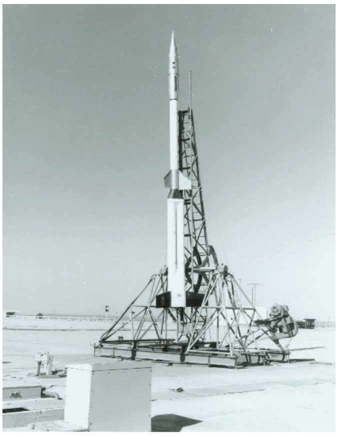

Figure 3: Long Tom, the first successful Australian sounding rocket developed by the Weapons Research Establishment.

Australia's first satellites

With its involvement in NASA space tracking and the sounding rocket programs at Woomera, by 1960 Australia was considered a leading spacefaring nation (Poirer, 1960). In 1967, the confluence of defence and scientific interest in the upper atmosphere that had helped launch Australia into space activities, enabled the development of its first satellite, Weapons Research Establishment Satellite-1, (WRESAT-1).

WRESAT's origins lay in a joint US/ UK/ Australia defence research program known as Project SPARTA (Special Anti-missile Research Tests, Australia), which was conducted at Woomera in the mid-1960s. Ten US Redstone rockets were brought to Australia for this program, but ultimately only nine were needed. The United States' SPARTA team generously donated the spare vehicle to Australia, so that the country could launch its first satellite (Morton, 1989; Dougherty, 2013).[2]

The WRESAT satellite was developed and constructed by the WRE, with the Physics Department of the University of Adelaide providing the scientific instrument package. This was designed to complement the WRE/ University of Adelaide sounding rocket program, providing a comparison from orbit to the data obtained via sounding rocket. (Lloyd, 1988; Dougherty, 2013).

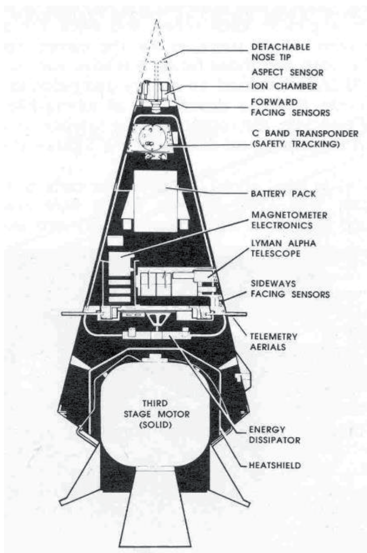

Figure 4: Cutaway view of WRESAT-1, showing its interior layout.

WRESAT-1's successful launch on 29 November 1967 gained Australia entry into the 'Space Club' as one of the earliest nations to launch its own satellite.[3] The battery-powered satellite operated successfully for five days, providing useful data for comparison with sounding rocket results.

2 Redstone vehicles had been used to put both the United States' first satellite into orbit, and its first astronaut, Alan Shepard, into space on a suborbital flight

3 Australia's place in the order of national satellite launches is a complex issue. It is more fully discussed in Dougherty, 2017

In 1968, the WRESAT team received Fairchild Australia's Planar Award for outstanding achievements in the Australian electronics industry. All those involved in the program anticipated that there would be further WRESATs. However, having gained the international kudos of a national satellite launch, the Gorton government had no interest in funding further satellites and WRESAT-1 was never to be followed by WRESAT-2 (Dougherty, 2013).

Although it was the first to be completed, being commenced in March 1966 (before WRESAT was even on the drawing-board), Australia's second satellite, Australis-OSCAR 5 was not launched until 1970. The world's first amateur radio satellite created outside the United States, Australis was the brainchild of a group of students at the University of Melbourne, who had been tracking the Project OSCAR (Orbiting Satellite Carrying Amateur Radio) amateur satellites. Its design incorporated several innovations for a small satellite, including the first use of a passive magnetic attitude stabilisation system and the first command system, enabling the satellite to be switched on and off, thus saving its limited battery power (Mace 2017).

After several delays in finding a launch for the satellite as part of Project OSCAR, Australis finally made it to orbit on 23 January 1970. It was designated OSCAR 5, as the first in a revived amateur radio satellite program under the newly formed Radio Amateur Satellite Corporation (AMSAT). Launched in conjunction with a NASA weather satellite, Australis-OSCAR 5's high orbit means that it will remain in orbit for approximately 1,000 years (Mace, 2017).

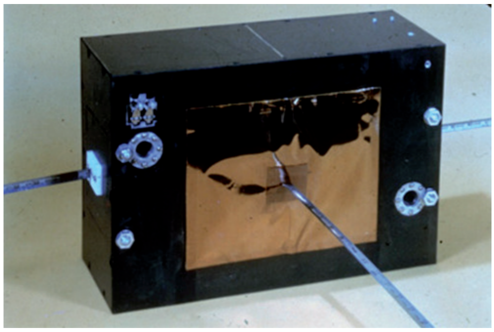

Figure 5: Australis-OSCAR 5 ready for launch. Note the antennae made from steel measuring tape.

Lift-off from Down Under: Europa and Black Arrow

In 1955, Britain commenced the development of Blue Streak, a medium-range ballistic missile intended to be tested at Woomera. The WRE undertook a massive extension of the Range and its facilities to accommodate the program. However, whilst in development, Blue Streak became essentially obsolete as a weapon and was cancelled in 1960. This resulted in serious embarrassment to the British and Australian governments (Morton, 1989; Hill, 2001).

In order to recoup its investment on the missile, the British government proposed it to European nations as the first stage of a collaboratively developed launch vehicle that would provide an independent satellite launch capability for Europe. Out of this proposal grew the European Launcher Development Organisation (ELDO). Britain provided the Blue Streak missile as the first stage for ELDO's new Europa launcher. France provided the second stage; West Germany the third stage and Italy developed the test satellite the vehicle would launch. Australia provided the launch pads at Woomera that had been originally developed for the Blue Streak missile, while Belgium and The

Netherlands provided the electronics and downrange tracking station at Gove, in the Northern Territory (Krige and Russo, 2000).

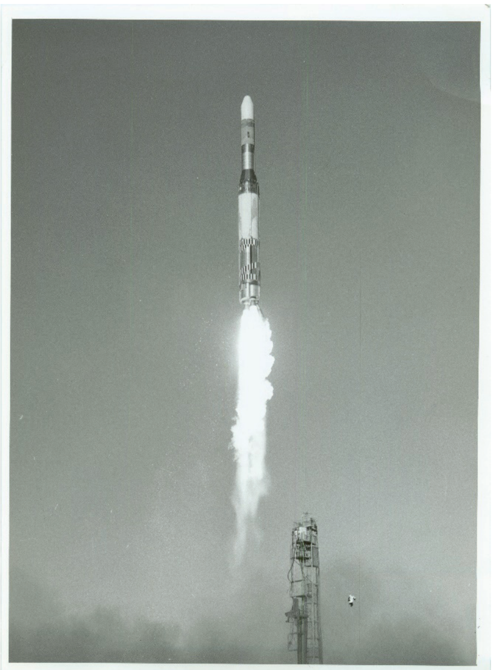

Figure 6: Europa F-8 ELDO launch from Woomera in November 1968.

Some critics considered this consortium approach to launcher development a recipe for disaster (Krige and Russo, 2000), and despite ten test launches from Woomera between 1964 and 1970, ELDO was never able to successfully launch a satellite from Australia. After Britain withdrew from ELDO in 1968, leaving France the dominant partner, the ELDO program was transferred to the French launch facility at Kourou, in French Guiana, in 1970. The program was, however, no more successful at Kourou and ELDO collapsed in the early 1970s (Krige and Russo, 2000; Hill, 2001). The European Space Agency (ESA), was born in 1975 from the ashes of ELDO, and it can be argued that it was understanding the mistakes made by ELDO allowed ESA to operate successfully and become one of the world's major space agencies.

After withdrawing from ELDO, Britain made one final attempt at developing its own satellite launch vehicle, designated Black Arrow. Derived from the reliable Black Knight defence research rocket used at Woomera for several years, the Black Arrow program was cancelled for financial reasons shortly before its fourth test launch. However, as the vehicle was ready, this launch was allowed to proceed.

On 28 October 1971, Black Arrow R3 successfully placed the Prospero satellite into orbit, the second satellite launched from Woomera. Despite this success, the Black Arrow program was not re-instated, and the United Kingdom remains to this day the only nation to have developed a satellite launch capability only to then give it up (Hill, 2001).

Australian adoption of satellite applications

The first applications satellites, so called because they apply the advantages of an orbital perspective to assisting with tasks on Earth, were launched by the United States in 1960. By the latter part of that decade, communications and weather satellites were beginning to become part of daily life, while Cold War militaries and maritime commerce were utilising the first navigation satellites.

Recognising the advantages of space applications for a vast and sparsely populated country, Australia was an early adopter of these satellite technologies. Today it is considered "one of the world's heaviest and most sophisticated users of space services" (CSIRO, 2015).

Australia became a founding member of the International Telecommunications Satellite (INTELSAT) consortium, which was created in 1964 to provide a global satellite telecommunications network. Australia would become INTELSAT's sixth-largest shareholder and play an important role in the control and monitoring of its satellites (Barrett, 1991).

Figure 7: The original Cassegrain horn antenna at the first Australian INTELSAT satellite Earth station in Carnarvon, Western Australia.

In the late 1970s, Australia also became a founding member and major shareholder of the INMARSAT (International Maritime Satellite) consortium (OTC, 1981), while Australia's first national domestic satellite communications system, AUSSAT, was established at the beginning of the 1980s. The first AUSSAT satellites were launched in 1985, but the system was privatised in 1992 to become the Optus communications company as a competitor to Telstra. INTELSAT and INMARSAT were also privatised within a decade of AUSSAT's privatisation, ushering in a new global telecommunications regime. (Dougherty, 2017).

The Bureau of Meteorology installed its first weather satellite image receivers at the beginning of 1964, which had an immediate and profound impact on weather prediction in Australia. The first satellite photo showing the whole of Australia in one image was received from NASA's Applications Technology Satellite-2 in 1967 (Griersmith & Wilson, 1997). Australian meteorologists have remained at the forefront of the interpretation and application of weather satellite information, and today receive data from Japanese, Chinese, NASA and NOAA (National Oceanographic and Atmospheric Administration) meteorological satellites to provide weather predictions and support climate change research (Dougherty, 2017).

Remote sensing, which uses satellites to look down on the Earth to understand and manage the environment and natural resources, was also a field in which Australia was an early adopter and an important pioneer (McCracken, 2008). Groups within CSIRO and the mining industry began using data from the Landsat-1 satellite not long after its launch in 1972. An archive of Landsat images of Australia was established in 1975, and the first Landsat receiving station outside the United States was opened near Alice Springs in 1980 (McCracken, 2008). Suitably upgraded, this facility now receives data from NASA, NOAA, French and ESA satellites, in addition to the Landsat series (Dougherty, 2017).

Management of early Australian space activities

Australia's initial involvement in space activities came about, not in response to a deliberate decision by the government to engage with space (as was the case with other nations), but as a result of external factors (in the case of space tracking) and the perceived requirements of the defence sector (in the case of the sounding rocket programs). Consequently, there was from the outset, no government commitment to the idea of a national space policy or a co-ordinated national space program (Dougherty, 2017).

Proposals for the establishment of a national space program from the Australian Academy of Science and the WRE were rejected across the 1960s as too costly. (Dougherty, 2017). Neither the Menzies Government, nor its successors, saw the need to establish a national space program or invest in the space sector, beyond those space applications that would provide a national good benefit or support defence and national security (Dougherty, 2017).

Although there was some Cabinet level discussion in the early 1960s about allocating the management of Australian civil space activities to a single government department or entity such as the CSIRO, bureaucratic infighting brought these proposals to nought (Dougherty, 2017). The WRE, with its management of Woomera, the NASA tracking stations and the Australian sounding rocket program, effectively became a de facto space agency, although the Bureau of Meteorology, OTC and CSIRO continued to manage their own space-related activities independently.

Consequently, when Britain decided in 1970 that it would cease weapons testing at Woomera in 1980, there was no space sector 'authority' to argue against the Australian Government's decision to cease the sounding rocket program and wind the Range down, since it had no particular use for the facility.

This resulted in a doldrums period from 1975 until the mid-1980s, by which time the development of the AUSSAT satellite system had sparked a new interest in developing a national space industry.

Making Space for Australia

The establishment of AUSSAT, coupled with a growing use of space applications (particularly remote sensing), generated a new enthusiasm in Australian industry for the possibility of becoming a major supplier, or even prime contractor, to future generations of AUSSAT or other national satellites.

In response, the CSIRO Office of Space Science and Application (COSSA), was established in 1984 and quickly became a driving force in developing Australia's expertise in remote sensing. (McCracken, 2008). Under COSSA's leadership, three remote sensing instruments were developed that flew successively on European remote sensing radar satellites ERS-1 (launched 1991), ERS-2 (launched 1995) and Envisat (launched 2002) (Dougherty, 2017).

The Hawke government commissioned a report from the Australian Academy of Technological Sciences, into whether Australia should establish a space industry. The outcome of the Academy's review was presented in the 1985 report *A Space Policy for Australia*, also known as the *Madigan Report*, after the Chair of the working committee, which put forward the basis for a comprehensive national space policy. It recommended that a national space agency should be established, to support the development of a national space program and a local space industry.

The Hawke Government, however, did not fully adopt the report's recommendations. Although it created the Australian

Space Office (ASO) in 1987, this was not an independent agency, as recommended by the report, but a unit with the Department of Industry, Technology and Commerce, specifically focussed on developing an Australian space industry: Its slogan was "Making Space for Australia". The ASO was also critically underfunded for the tasks required of it, having an annual budget of around $4 million, instead of the $25 million recommended in the report (Madigan, 1985).

Figure 8: The Endeavour Space Telescope (in cylinder front left) in the cargo bay of the Space Shuttle.

Despite these drawbacks, the ASO had some small successes, the best known of which was the Endeavour Space Telescope. Funded by the ASO, the Endeavour telescope was built by a new Australian space company, Auspace, that was spun out of research at the Mt. Stromlo Observatory. When first conceived, Endeavour was a cutting-edge ultraviolet space telescope. However, its space qualification flight on the US Space Shuttle was delayed as a result of the *Challenger* accident in 1986. By the time it had made two qualification flights, in 1992 and 1995, other instruments had already surpassed its performance and the opportunity for commercialisation was lost (Dougherty, 2017).

Commencing in 1986, several proposals were put forward for the development of a commercial spaceport in northern Australia, to gain a foothold in the lucrative satellite communications industry. Large satellites required launch facilities near the equator in order to place them in geostationary orbit. In addition, it was hoped to capture some of the multiple launches that would be required to service the multi-satellite constellations (some proposed to number many hundreds of satellites) in Low Earth Orbit that were planned for early mobile phone networks.

Locations on Cape York, around Darwin, and on various islands to the north of Australia or in Papua New Guinea were proposed, many planning to use newly available cheap Russian launch vehicles. However, none of these projects ever came to fruition came to fruition, nor did other proposals promoting the revival of Woomera as a launch site for polar-orbiting satellites.

Lost in space?

When the Howard Government came to office in 1996, it terminated the ASO and all its space-related projects, as the new government's view was that the space sector was like other high-technology industries and it was not necessary to allocate specific support for the development of a local space industry. It did, however, pass the Space Activities Act in 1998, the world's first formal legislation specifically covering commercial space launch operations. This provided a legislative framework under which proposals for commercial launch facilities could be regulated (Siemon and Freeland, 2010).

In addition to terminating the ASO, in August 1996 the Howard Government also restructured COSSA, creating from it a new Co-operative Research Centre for Satellite Systems, responsible for a new small satellite program, FedSat (Federation Satellite). FedSat was designed to build on existing national research experience and industry capabilities through the production of a small demonstrator satellite as a celebration of the centenary of Australia's Federation. Although construction delays meant that FedSat was not launched until 2002, the project was a modest success, with the satellite functioning until 2007 (Dougherty, 2017).

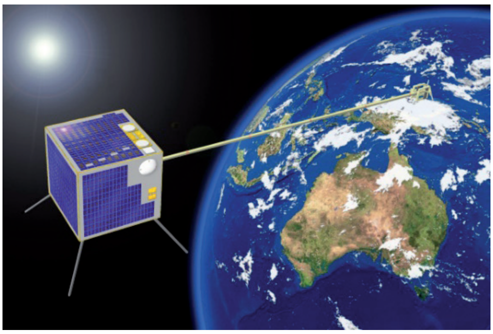

Figure 9: An illustration of FedSat in orbit above Australia.

Despite the FedSat project, the Australian civil space sector languished in the early 2000s, prompting one commentator to lament that Australia was "punching below its weight" in space activities (Kingwell, 2005). A growing call from the struggling Australian space sector for a national space policy and a national space agency, eventually led the Senate's Standing Committee on Economics to review the state of Australia's space science and industry sector. The outcome of this review was the 2008 report *Lost in Space? Setting a New Direction for Australia's Space Science and Industry Sector*. Like the earlier *Space Policy for Australia* report, it recommended the creation of an Australian space agency and a co-ordinated national space policy (Siemon and Freeland, 2010).

The Rudd Government, while not fully embracing the report's recommendations, established the Australian Space Research Program (ASRP) in 2009, which allocated $40 million to support technology demonstrator and education projects that could lead to viable economic programs for utilising space to the benefit of Australia.

Some of the projects supported by the ASRP did go forward to further commercial development. It also enabled the growth of Australia's now-recognised expertise in space situational awareness. In 2013 Australia's first formal space policy, the narrowly focussed *Australia's Satellite Utilisation Policy*, was released under the Gillard Government (Dougherty, 2017).

However, the ASRP was terminated and the Satellite Utilisation Policy left in limbo when the current Liberal government came to office in 2014.

The New Space Paradigm

Around the beginning of the last decade, a new space paradigm emerged. Sometimes referred to as NewSpace or Space 2.0, this entrepreneurial movement has been inspired by commercial space pioneers such as Elon Musk and Jeff Bezos and driven by young entrepreneurs who want to take advantage of modern miniaturisation and digital technologies. Over the past decade or so, these technologies have revolutionised what can be accomplished in space with relatively small budgets, enabling the production of very small, cheap, effectively expendable satellites that can be launched on light, cheap launchers. Satellites the size of a loaf of bread now offer capabilities that previously required a multi-billion dollar satellite launched on a multi-billion dollar rocket (Dougherty, 2017).

This Space 2.0 paradigm has been adopted very rapidly by the entrepreneurial space community in Australia. While some local NewSpace companies have already flowered and died, as is the nature of start-ups and entrepreneurial companies, others are now well established and forming part of Australia's 'new space age', with satellites in orbit and commercial products in the marketplace.

This rapid transformation of the civil space sector, with its entry costs now significantly lower than in previous decades, provides real opportunities for a wide range of Australian companies, especially small and medium enterprises, to become involved in the global space industry. The realisation that the Australian economy was failing to capture a significant share of a global space industry worth approximately $350 billion in 2017 (Bryce, 2017) led to a reappraisal of Australian space engagement by the Turnbull Government. It came to recognise the need for a national space agency to act as a 'front door' to the world for the Australian space sector.

Consequently, at the 2017 International Astronautical Congress in Adelaide, the government announced its intention to form the Australian Space Agency (Sinodinos, 2017), which came into being on 1 July 2018.

After sixty years that have seen the Australian space activity wax and wane, lacking policy direction and effective co-ordination, the formation of the Australian Space Agency offers the opportunity for this country to enter into a new era of Australian space activity, which has the potential to far surpass any previous achievements.

Acknowledgements

Figures 1, 3, 4 and 6 are original WRE photographs and diagrams provided by Defence Science and Technology Group. Figure 2 photo of monitor at Honeysuckle Creek tracking station by Ed von Renouard, courtesy of www.honeysucklecreek.net. Figure 5 courtesy of Owen Mace. Figure 7 photo by Graham Watts; courtesy of www.honeysucklecreek.net. Figure 8 NASA. Figure 9 courtesy of Glen Nagle.

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The Australian Space Agency

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Introduction

It is absolutely an honour to be here for the Royal Society of New South Wales and the Joint Academies Forum in what is a very timely and important gathering, and I appreciate the chance to be able to be here. I also pay my respects to the knowledge and traditions of the Gadigal people of the Eora Nation.

What I wanted to do today was give you a quick update of where we are with the Australian Space Agency. I also wanted to turn my attention to the recent announcement by the Prime Minister that Australia would join the United States on the "return to the Moon and on to Mars."

Establishing the Australian Space Agency

Nations establish space agencies for many different reasons. It may be to demonstrate global dominance in technological development. Other countries look to the inspirational capacity of science, and we're seeing that now with India inspiring a whole new nation of young graduates coming forward in that country. The Australian Government's case was absolutely clear that the purpose here was to diversify our economy. I think we've been surprised as well by the capacity of space to inspire this country.

So we set ourselves the purpose of transforming and growing Australia's space industry, to lift the broader economy and improve the lives of all Australians. We know as a small country we simply cannot do that without the global partnerships that we will need to participate in. This is one of the most commercially focused purposes of any space agency in the world.

There are some very important values that we used to establish the Australian Space Agency. We wanted to be known as a responsible citizen in space. We felt there was a real role for us, not just globally, but also in our region over time to be that very important voice for a rules-based order in space and to do our bit at the global table.

We have the entrepreneurship, we have the "can do" attitude, we absolutely have the ideas and the talent, we have the capacity to run through the legs of giants — we've just got a little bit of catching up to do, and these are some of the values that absolutely run through the Agency.

In terms of what we're responsible for, it is civil space policy and strategy for the regulatory piece. We coordinate civil space activities, and we are also looking to inspire and engage the Australian community. This is within the broader context of supporting the growth of the Australian space industry, and not just growth, we truly want to see and facilitate, and encourage and catalyse as much as possible a transformation of the industry.

Year one for the Australian Space Agency

One of the first things we needed to do was to modernise our legislation. Very early on, after the establishment of the Agency in July, in August 2018 our team managed to update the Civil Space Act into the *Space Activities Amendment for Launches and Returns*. A couple of key things in there: we needed to make sure our rules and laws covered the launch of spacecraft from aircraft, something it didn't actually anticipate, and also high-powered rockets. The Agency has been in consultation around the country and has written the rules for that, and we're now working with the industry on implementing those rules.

We set ourselves the goal of engaging the nation. We actually set ourselves the goal of five million Australians in our first year would hear, see or read about the Agency. We felt that one in five was actually a pretty good target, but we blew past that literally in the first few weeks. By October 2019 we now have touched 110 million Australians. Now, I know we don't have 110 million Australians; it means that people are seeing and hearing about this new endeavour multiple times.

Importantly, if you're going to transform an industry, you need to get out to where the industry is which is in the states and territories. We have worked very extensively with the Premier's and First Minister's Office in each of the states and territories. In fact in our first year, every 12 weeks myself, my deputy and a team visited every state and territory to engage in that dialogue because the states and territories themselves need to have strategies for the growth of high-tech jobs.

We set ourselves the goal of stimulating an investment of $2 billion into the space sector, a billion of which we wanted to come from outside Australia into the country. This was not about moving around money inside the country because it's the investment of capital in the sector that truly grows jobs. We set ourselves that goal to do that in the next few years — we're already at $1.6 billion of forward-projected capital project pipeline, and that includes R&D investment, and $700 million of that is inbound capital.

If we looked at that two years ago, it was literally just a couple of hundred million. So this investment of capital is also the world and others taking the signal from the Australian Government and the stimulus that we're seeing around the states and territories, and saying Australia is serious about space. As a result, it has created a good platform for investment.

One of the things that the nation told us is to do what is not being done. We love what CSIRO is doing, we love what Geoscience Australia is doing, we even like what ACMA is doing (the regulator), but we need one door. We need one door, one voice — we're missing out on these opportunities that can truly only be brokered from government to government and through agency to agency.

We're now partnering with multiple agencies around the world. That's as well as the most recent agreements that we've had in the last month with New Zealand, DLR, and we've updated as well with ESA and the Italians. So we really are starting to open doors for the purpose of our researchers and industry to walk through those doors.

We're at the cusp of a transformation from the investment in space by governments. Decades ago it was 80 per cent government funding, 20 per cent commercial. That has now completely flipped around and we're seeing government still having a very significant role here. We're seeing the commercial entities now dominating the investment, and we're seeing the industrialisation of low-Earth orbit in itself, so we knew we needed a mechanism to be able to join together with industry partners to be able to grow and transform this industry.

As part of this we formed the Statements of Intent and Cooperation. These basically outline our strategy, and ask industry what they are going to do to support the objectives of the Agency, what they are going to do to invest in internships in R&D and in establishing facilities here in Australia, and what they are going to do to stimulate jobs. I think these have helped generate that interest that we're seeing and the investment.

National civil space priorities

We are a small country, so we need to focus on those things that work well for us and where our competitive advantage is.

- First of all; *position navigation and timing*. Australia has made the commitment to bring our positioning in our maritime, our land and our airspace up to 10 centimetres accuracy. Importantly, the decision to move to precise positioning in our capital cities where we can take additional corrections from the mobile phone towers and get down to perhaps three to four centimetres. That means you can automate transport, you can do all sorts of things, so a really wonderful start to that investment. Geoscience Australia will do that.
- *Earth observation*: the next generation of communication, laser optics, laser radio, some extraordinary work there.
- *Space situational awareness*: taking our role here in the Southern Hemisphere as important.
- *Leapfrog R&D*: was actually a grab bag for all of the things that we're really good at, but we need to be world class and out there in the supply chains.
- *Robotics and automation*: a clear leader for Australia.
- *Access to space*: when we first started it was like "It's not about rockets," but it is about rockets now.

In terms of the NASA announcement, we will join NASA to "return to the Moon and on to Mars." It's a $150 million program over five years. We'll do demonstrator projects that showcase our capabilities. We'll also work on some very significant major projects and support access of companies and researchers into the supply chains.

One of the key things of going back to the Moon and Mars will be the search for water. You need an awfully big rocket now to do this. One of the rockets; the Space Launch System, is a payload of 26 tonnes. This is the NASA program Artemis 1 first of all orbiting the Moon, so taking human spacecraft, then taking humans in an orbit around the Moon, then building out the components of the Gateway, the power propulsion, the human habitat, and then also making sure that there's a lunar lander on there. Then Artemis 3 will be the crewed mission to the Gateway and the lunar surface from 2024.

The next phases of this, and Australia has the capacity to join in this up to Artemis 7, this is really living and working now on the Moon and testing those technologies and things that we will need to go to Mars. In December 2013 the LADEE mission noticed that there was water vapour coming particularly connected with meteorite showers, so one of the first tasks of the mission to the Moon will be to see if we can tap into that water that sits possibly below the surface.

Conclusion

Overall, we're working very hard to build an Agency of which Australia, hopefully, will be proud. Thank you.

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CSIRO: our roadmap for space

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Introduction

CSIRO, Australia's national science agency, was established more than a hundred years ago and has 75 years of space science heritage. Fifty years ago CSIRO played a key role in supporting NASA's Apollo 11 mission to the Moon.

Today the $350 billion global space market is growing, NASA is calling for a return to the Moon with international participation, and Australia is uniquely positioned and eager to take advantage of this opportunity. The Australian Space Agency was established with the goal of tripling the size of the Australian space industry in terms of economic value, and creating up to 20,000 jobs, by the year 2030. Investing in R&D to assist Australian industry growth and solve Australia's greatest challenges is CSIRO's core role. CSIRO aims to be a key technology partner to the Australian Space Agency, driving technological innovations and providing science and research facilities that will support the Agency's industry growth goal.

CSIRO hosts several national space facilities, including the Australia Telescope National Facility, or ATNF, and the Canberra Deep Space Communication Complex, or CDSCC. The ATNF includes three radio telescopes in New South Wales at Parkes, Narrabri and Mopra, near Coonabarabran, plus the Australian Square Kilometre Array Pathfinder in Western Australia, which is an array of 36 antennas.

Australia is uniquely positioned in the Southern Hemisphere to support international space missions through the provision of tracking and communication services. CSIRO was recently appointed to provide operational support for the European Space Agency's Deep Space Tracking Station at New Norcia in Western Australia. And CSIRO also manages the operations of CDSCC, which is one of three stations worldwide that make up NASA's Deep Space Network. CDSCC is currently tracking around 35 Deep Space missions, including the well-known Voyager 2 spacecraft. After 42 years Voyager 2 is now approximately 18 billion kilometres from Earth travelling through interstellar space, and due to Voyager 2's southward trajectory out of the solar system and its distance from Earth, the CDSCC tracking station and the Parkes radio telescope are now the only two facilities in the world that are capable of having contact with that spacecraft.

CSIRO has had world-leading capabilities in Earth observation data analytics, calibration and validation for decades, which are coordinated by the CSIRO Centre for Earth Observation. This centre is also home to CSIRO's first CubeSat, CSIROSat-1, which is under development in partnership with Adelaide space technology company Inovor Technologies, and is due to be launched from the International Space Station in 2021.

The Centre for Earth Observation also manages CSIRO's 10 per cent capacity share of the UK-operated NovaSAR-1 satellite, which is expected to become fully operational in 2020. NovaSAR-1 is a synthetic aperture radar (SAR) satellite which can operate day and night, and through smoke and cloud, making it well suited to assisting with managing many of our national bushfire and flood challenges. CSIRO will operate our share of NovaSAR-1 as a national facility for all researchers to access.

Space Technology Future Science Platform

In addition to these activities, CSIRO's newest space research program is the Space Technology Future Science Platform, or Space FSP. The aim of this program is to further CSIRO's space capabilities by identifying and developing the science to leapfrog traditional space technologies, and to identify new areas for Australian industry to work in — areas in which we can leverage our existing space and terrestrial capabilities for new space applications, and in which Australia can be globally competitive in order to support the Australian Space Agency's industry growth goals.

The Space FSP was established in late 2018 with a program lifetime currently of three and a-half years. Over the past 12 months the Space FSP has already initiated 23 projects with a total program value of over $21 million already. Its activities focus on the National Civil Space Priorities outlined by the Australian Space Agency and address a wide array of opportunities, including:

- advanced satellite technologies, particularly in relation to CubeSats and small satellites, including power, control and sensing systems, structural technologies and onboard data processing
- remote operations and in situ resource utilisation, including new technologies for off-Earth resource exploration and synthetic biology approaches to resource extraction
- human factors and biomedical technologies to better support human space missions
- Earth observation data analytics and applications development
- new high bandwidth space communication technologies using optical and terahertz band links, and
- new techniques for space object tracking.

Current projects

The following section highlights a few examples of the projects underway through the Space FSP.

NASA is planning to return humans to the Moon by 2024 and establish a permanent human presence there, and the Australian Government recently committed to supporting the Australian space sector to participate in this mission. There is significant interest in accessing valuable lunar resources, particularly water ice, to support human missions to the Moon. Remote mining operations and asset management are already a strength of the Australian resources sector, and applying this to the space environment through in situ resource utilisation is a challenge that Australia is looking to play a role in.

The Space FSP currently has four projects in the robotics, remote operations and resource utilisation area, and one of these projects is developing a predictive analytics software platform to produce 3D resource models of the Moon, asteroids and other bodies to support future prospecting and resource utilisation planning. The Space FSP is also looking at potential new opportunities relating to providing space analogue facilities here in Australia, which encompasses everything from Mars surface analogues to microgravity facilities to digital twins.

The Space FSP is also leveraging CSIRO's existing Earth observation expertise and facilities to make significant developments related to the accessibility and application of satellite-derived data. This includes: utilising the NovaSAR-1 satellite to grow SAR expertise nationally and drive the uptake of SAR data in Australia; and building on CSIRO's data cube expertise to create high-performance data processing infrastructure to better analyse, integrate and utilise multiple Earth observation data types including hyperspectral and lidar data. This latter project aims to improve satellite data accessibility and utilisation for a broad range of applications, from agricultural crop and freshwater algal bloom modelling to carbon stock and greenhouse gas monitoring.

Globally, rapidly growing Earth observation data volumes are an ongoing challenge both with regard to effective handling and use of the data for various applications, and with respect to the increasing bandwidth required to downlink the data from satellites. Under another Space FSP project, the CSIROSat-1 satellite will provide a platform to demonstrate sophisticated onboard data processing techniques to reduce the amount of data needing to be downlinked from the satellite.

In the materials and manufacturing domain one of the Space FSP projects is demonstrating novel additive manufacturing techniques — namely electron beam melting and cold spray — for Invar, which is a low coefficient of thermal expansion alloy, to create metallic composite components, including precision optics mounts, for CubeSats. Using these manufacturing techniques, the mechanical properties of a composite component can be tailored in different locations on that component.

With regard to space biomedicine and space life sciences, experimental "labs in a cube", based on the CubeSat format, are a permanent fixture on the International Space Station (ISS). One of the Space FSP projects is developing a new "lab in a cube" testing platform called an Optocube, which will enable human cells, particularly bone cells, to be studied on the ISS. The Optocube is unique in that it will use light as the only stimulus to control cells and to detect results, so the experiments are able to be completely contactless.

The Space FSP is also in the preliminary stages of exploring opportunities related to bio-manufacturing for healthcare in space, and space agriculture.

Future pathways

The projects mentioned here are not an exhaustive list of the Space FSP's activities. Furthermore, the Space FSP currently runs until mid-2022 and it will continue to invest in new collaborative activities over the next two and a half years.

All of these investments of course produce the best outcomes when they are done in partnership with other research organisations and with industry, which provides the path to impact for these new technologies, and the Space FSP welcomes opportunities for new collaborations. CSIRO will also continue to partner on other R&D programs to build Australian space industry capability, like the DMTC High Altitude Sensor Systems Program and the SmartSat CRC.

CSIRO looks forward to continuing to work closely with the Australian Space Agency and Australian industry on the next giant leaps to the Moon, Mars and beyond.

https://research.csiro.au/space/

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Seeing and sensing Australia (and elsewhere) from space

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It's really a privilege to be here speaking about this very briefly today at, as has been observed, a really opportune time.[1] I'm going to take you on a journey about remote sensing looking down.

We've heard about how inspirational it is to look at space. We've heard how inspirational space engineering and enterprise is, yet astronauts who go into space will almost always talk about how moved they are and inspired they are when they look back at Earth from space, when they observe Earth as a sole planet in space, a fragile beautiful place that we live. The image called 'Earth Rise' is famous. It was taken on Christmas Eve, 1968. It's said to be the most important environmental photograph ever taken.

Perhaps that's one of the reasons that many, many satellites have since been launched to observe Earth. We have constellations of satellites in low-Earth orbit capturing data, measuring our atmosphere, our oceans and our lands. That's produced things like images of Australia through programs like the Landsat satellite which celebrates 40 years of cooperation with Australia this year, or this week in fact — the Director of the United States Geological Survey is in Alice Springs.

The efforts are held together through international networks of people and infrastructure, symbolises by this dish in Alice Springs, painted with colours that are of significance to the native American people in the Sioux Falls area of the US. I would love to spend time talking about all the leadership that Australians have done in Earth observation, but not today.

What's really exciting about this area at this point in time? Everybody's heard about remote sensing satellites; but, frankly, the supply chain that links those satellites to decisions has never really matured. By the supply chain, I mean on the one hand we have satellites taking measurements, on the other we have people making decisions. Look at something like positioning satellites: when I get into an Uber, the driver and I are both using a satellite to know where we are; neither of us knows about it or has to know about it. There's nothing equivalent in this land: remote sensing is looking down.

We're starting to understand what that supply chain looks like and it's starting to transform the way in which we're using and will use these satellites and their information. It hasn't happened before because it's more complicated and more difficult to do, but after more than 10 years of effort, we're just getting there now.

The first step is that now these satellites are not science missions anymore, they're synoptic operational missions capturing high science-quality data, run in an ongoing sense by the European Space Agency, the United States Geological Survey and other international space organisations. The

1 This is an edited version of the transcript of Dr Lewis's talk.

data are free: they're unlicensed so they're open licensed, anyone can leverage them, and they're going to continue; that makes a huge difference.

What that does, though, is produce a problem with data; these data are not easy to use. They contain a lot of noise, they have clouds in them, so the next step that's being taken — based on some really leading work from Australia and other countries over the last decade — is that the satellite operators are now starting to produce these data, not as raw images, but as ready-to-use measurements, and this concept of analysis-ready data has emerged and been endorsed through the international community where these satellites are producing primary measurements of the land surface, the reflectance of land surface, its temperature, its roughness. The word "measurement" is really important because it's allowed this community to start moving into a quantitative science field, rather than a qualitative analysis.

That then leaves a huge problem with big data: how do you actually manage all the data that we now have available and ready to use? An Australian innovation, the Open Data Cube, has actually provided the solution to that, so now we're seeing something that Australia made being taken up globally. A satellite sees the earth as a bunch of strips which are continually building up over time. It's not a good way to work with data.

Computers like to work with data in this sort of format, and so the Open Data Cube paradigm — you'll hear about the Data Cube if you talk to anyone in Earth observation pretty much globally now — is that the data are restructured or indexed into something which is geographically regular and stacked as a time series. Every pixel in every image is calibrated, it's flagged according to whether it's a good observation or has a cloud in it, and the time series is used so that one can integrate or differentiate through time — a bit of an inspiration from the astronomical community — and actually extract far more information than has ever been possible before.

This was invented in 2013 when these data were processed in this way to produce the first map of Australian surface water for the National Flood Risk Information Program that was running at that time. The map — which shows areas where there's rarely water in red, they're flood plains, through to areas where there's persistent water, in green and blue — was a world first; nobody had done anything like this before. There's something like 10^14 actual observations going into that particular map.

It's now a continental product which is updated every month as new data come in, with wide ramifications, and underlying that are a series of measurements.

This supply chain is starting to work; it's starting to be filled out. The last part is how that connects with decision makers; not just decision makers in government, but across all sectors, and that's a process of building opportunities that can allow a user community — an *ecosystem* is the emerging word me — an ecosystem of users to engage with the opportunities presented by these continental products that have been produced, a little bit like the weather service produces maps of surface temperature for the day.

It's not just about water — what I'm showing here is a little black square in the middle of the image. For that black square what's being measured from the same satellites, using an algorithm developed in Australia, is how much green vegetation there is, versus how much bare earth or dry vegetation, and that's been tracked through time from the late 1980s through to present, showing a signal, and the signal corresponds to a cropping regime, a wheat crop, and then it changes in the early 2000s through to a more persistent green as they change the crops to almonds, the implications for water use. The important thing is that that analysis can be done everywhere in Australia and every day, and provided to everyone. Geoscience Australia has been funded to maintain that as an operational capability going forward, and that's Geoscience Australia's Digital Earth Australia program.

We now have a really exciting opportunity where this supply chain, as I said, is starting to work. Just what does that mean? Making space for Australia; what does it mean in this context? I think it has a number of implications.

First, government. For government it means there starts to be this regular and available and authoritative evidence base that can inform decisions in the environment in a way that's never been done before. The New South Wales Government produces a map every month, a state of the drought report. It shows for every parish in New South Wales the status of the farm dams, compared to normal, and it's based on an analysis of those satellite data which are automatically generated; it compares how much and how big the surface of the dam is to normal, based on the history, and produces a map, adds it up by parish to make a map across the state.

Second, things which were not anticipated when the satellites were launched are now starting to have real impact. For researchers it's really cool. Researchers in this area traditionally spent 80 per cent of their time wrangling data, correcting data, finding it, getting it, putting it on their computer and correcting it.

I got some feedback from Norm Campbell, who ran Maths and Stats in Perth in the CSIRO when we provided him some ready-to-use calibrated data. He got it straight away. This saved time and let him focus on the research question, "What are the processes that are happening and how are people interacting with those processes?" — the hard questions.

Third, more enthusing: students. We're now at a point where students who are not remote sensing specialists can engage with these data sets and do things that they just couldn't do before. A couple of years ago Emma Johnston, at UNSW, and I got together and created a little collaboration, and Ana Bugnot, her student, produced an assessment of the water quality in all the estuaries around Australia and published it, and someone in the conference that Emma was at took a photo and sent it back to me saying, "Check this out. They're using our data to do this wonderful research." So students can now engage with this and use it as a resource, and they're doing that.

And, fourth, more exciting still, consortia of researchers are starting to use the same data and do things that haven't been done before. There is a methodology for mapping mangroves that's been agreed by a national consortium, and we now have an annual update of the mangroves in this particular part of the coast, which changes through time and expands up till about 2013, and then in some areas of the coast there was a massive dieback as the coastal area contracts to be virtually nothing, all of which can be quantified, but then it can be scaled up so that could be done for the whole country.

So for the first time, having spoken about it for decades, we now have an national assessment of mangroves. Graphs, from the late '80s to the present, show how the total area changes, and how the density of canopy cover changes, so we have national assessments of things which previously were theoretically possible, but completely unaffordable, even if they could agree on the methodologies.

It's interesting to see what this means for industry, which can now engage with these data sources, whereas previously it was too expensive and too difficult. The data may have been free and open, but actually having the expertise and going through the process of getting them, working with them, was an overhead that small-to-medium enterprises, like Spatial Vision, wouldn't contemplate for a normal size product. They could now get these data from Geoscience Australia and leverage them as they see fit.

Other industries are more exciting: a company called Cibo Labs based in Toowoomba uses a map of an agricultural product on an almost daily update by Geoscience Australia which shows how much of the ground is bare earth, how much is green vegetation, and how much is dry vegetation. They take that as an input, then they make it into a pasture biomass map, and add that up by paddocks, and then they feed it to their farmers as an app, as a piece of information that they can use to modify and optimise their land management.

When there was a closure to the US Government on Christmas Eve, 2018, we had a bit of a glitch at our end, because we rely on them. Cibo noticed it straight away and we had somebody fixing it, actually using this in an operational context in the commercial setting. So innovators are getting into these datasets.

I think equally exciting is what it means for these small satellites. We heard earlier about companies putting up tiny satellites. At a conference in California in August 2019 companies like Planet, who make these tiny satellites, were talking about how they're working and what they're doing. They demonstrated that they will use the infrastructure of these highly calibrated government satellites as a baseline, so they will take the weekly satellite observations from the United States Geological Survey, or in this case, from the European Space Agency, and mash their data very accurately, so they can then provide one-metre resolution every day, and they have the authority to correct the data in a way which is consistent with the government science agencies. This is a capability that is relevant to anybody who's using these satellite data.

Most importantly, what does it mean nationally? It means we have billion dollar economies growing on these data. We have a lot at stake here and our primary interests over the last decade or so has been to ensure that these data flows continue. There are at least three ways in which we can do that. We need leadership in international forums, so this week in Canberra there's a Ministerial Forum of the Group on Earth Observations hosted by Australia, multiple international delegations there, and that's a good thing. That's talking about Australia giving back and then helping the community.

I have co-chaired something with Alex Held from CSIRO on the most powerful committee on this Committee on Earth Observing Satellites for a couple of years where we get to talk to people who operate billion dollar budgets, unlike us, with satellites.

We must also look at investing in the upstream section. We have to get something into space so that we've got a real seat at the table with these capabilities. Instruments on satellites that we need and that grow our industry and that are useful to others are the way to do that.

Most important of all, or most impactful of all, is contributing our ideas internationally. We're now taking algorithms, such as the water algorithm we use in Australia, and applying them to whole new continents, such as Africa, as of last weekend. We have taken the software into the Amazon Cloud and now we have the ability to go to Tanzania and look at how water use has changed there. We can expose that to anyone in Africa and they can use it as they see fit and guide its future development.

We're at a really exciting time in Earth observation looking down; not all the inspiration's up. My counterparts in NASA only have $3 billion budgets, but they're still great people to work with when they've got three orders of magnitude more money than you have, you don't have to do much to have some good friends. Thank you.

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The limits of law: challenges to the global governance of space activities

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Abstract

The development of space-related technology since the dawn of the 'space age' in 1957 has given rise to many new and exciting possibilities. Humankind is now seeking to embark on a broad range of space activities and the utilization of this technology forms an integral element of the global society, such that the world is dependent upon constant and unimpeded 'access' to space. Yet, the existing international legal and governance framework, largely developed in a very different era of space activities (1960s–1980s), is now under strain to provide the necessary certainty, standards and protections to appropriately address specific uses of space that have emerged due to recently evolving space technologies. This gives rise to a number of significant challenges for the ongoing global governance of the use and exploration of outer space and, in particular, humankind's interaction with, and dependency on space-related technology. Important questions arise as to how to address these challenges in a way that will enable humankind to continue to use space for peaceful purposes and to garner significant benefits through such use for the benefit of the global society. This article highlights some of the major challenges that arise and outlines important factors that must be considered in developing appropriate legal, regulatory and policy frameworks for future space activities, so as best to serve the interests of current and future generations.

The complexity and ubiquity of space

On 4 October 1957, a Soviet space object, Sputnik I, was launched and subsequently orbited the earth over 1,400 times during the following three-month period. This milestone heralded the dawn of the space age, the space race (initially between the Soviet Union and the United States), and the legal regulation of the exploration and use of outer space.[1]

Since then, some fundamental international legal principles have developed that significantly improve the standard of living for all humanity through, for example, the facilitation of public services such as satellite telecommunications, global positioning systems, remote sensing technology for weather forecasting and disaster management, and television broadcast from satellites, coupled with many additional uses of space that are, and will be possible through

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the advent of the miniaturization of satellites.[2]

Furthermore, the scientific and exploratory nature of many space activities further enhances our knowledge of the universe in which we live, as well as the origins of the Earth and of humankind. We are now also looking at the prospect of establishing human settlements in space and further utilising and exploiting the natural resources of space that might ultimately be accessible to us.

Space is vital in terms of the world economy, strategic thinking, terrestrial military strategy, geopolitics, human rights, commercial enterprise, technological innovation and, frankly, the future of humankind. The impact of our use of space and the increasing range of space activities mean that law does and should have an important role to play in ensuring that such activities are carried out in an appropriate manner, with appropriate outcomes and benefits and for appropriate purposes. Moreover, the avoidance of a "tragedy of the commons" scenario[3] is crucial if humankind is to garner the maximum benefit from what space can offer.

Clearly, therefore, the prospects for the future use of outer space offer both tremendous opportunities and challenges for humankind, and law at both the international and national levels will continue to play a crucial part in this regard. It is in this context that this article sets out to briefly outline some of the various challenges ahead for legal regulation in this sphere.

Legal challenges posed by the development of space technology

Given the rapid advance of technology in so many spheres and the clear reality that, in many respects, the world is becoming "smaller" and increasingly "internationalized," there is an imperative to explore the fundamental design elements of supranational legal governance for issues of global concern — for example, the impacts of climate change, world poverty, the global commons and international criminal justice[4] — whilst also retaining a grounded view of their significant practical contemporary relevance.

Since the exploration and use of outer space is so impactful on this ongoing evolution, leading as it does to so many changes in the way that individuals, communities, cities, nations and the world operate and exist, this is equally the case when it comes to the regulatory and policy frameworks for space activities. The sheer pace of change and the broadening of potential activities in outer space dictates that we need to continually monitor the scope and content of this framework, whilst at the same time recognising that, at least from a strictly legal regulatory perspective, it will not (ever) be possible for the law to keep up with these changes.

This is highlighted, for example, by the interaction between space technology and another area of great relevance to future global/international regulation: that of cyber law and cyber security. It is important to recognize that the important issues that arise from the continuing development of

2 See Freeland (2019).

3 See Hardin (1968). For a discussion of the implications of the tragedy of the commons to the use of outer space, see Freeland (2017a).

4 For an example of the interplay between the use of space technology and the promotion of international criminal justice, see Freeland & Jakhu (2018).

cyber technology are increasingly relevant for the regulation of outer space, given the increasing rush towards a "digitization" of space activities. Just as there have been past lessons for space law in considering the legal regime established for air space, so it is important for the future development of space law to understand the complexities — from a jurisdictional, technical, commercial, societal, cultural and security-related perspective — that arise with respect to the use and regulation of cyber space.

There are clear parallels between the two regimes of outer space and cyber space, not only in considerations impacting on the law-making side, but also due to the seemingly endless development of technology that results in the activities of these two realms becoming ever more interdependent. In many respects, they act together in the one ecosystem, each reliant on the other for their respective efficient functioning, development and ongoing operational viability, not to mention the important associated national security considerations.

Indeed, it is increasingly necessary to design space infrastructure with a clear reference to the cyber-related elements associated with the implementation, utilization and application of that infrastructure. In this regard, it is somewhat curious that, in quite of number of countries, Governments have devoted considerable resources towards the establishment of systems designed to protect the cyber capability and operations of that country, but have not perhaps been as cognizant to devise similar protective systems for their space assets.

Instead, a different mantra — one involving the call for defensive space weapons — seems to have been accepted as the most appropriate (and in some cases, only) way in which to protect important space infrastructure. A closer consideration of the interplay between cyber capability and space operations is an equally (and perhaps more compelling) strategy to work out appropriate national security measures to minimize the possibility that space assets might be compromised by the actions of other States.

Bearing in mind the rapid development of space-related technology, and the legal challenges that this represents, it is pertinent to reflect on the fact that, in 2017, we celebrated the 50th anniversary[5] of the first — and most significant — of the United Nations space treaties, which is usually referred to as the Outer Space Treaty.[6] During that celebratory year, this author was invited to give a number of keynote speeches at various events to commemorate that important event. In the course of preparing for those speeches, this author had cause to look at an important collection of essays entitled *Outlook on Space Law over the Next 30 Years*, which was published on the occasion of the 30th anniversary of the Outer Space Treaty in 1997.[7]

It is interesting but perhaps not surprising that, barely two-thirds of the way through the second 30-year period following the finalization of the treaty, virtually all of the "possible"/"maybe"/"perhaps" innovations in space canvassed in that book are already a reality or near reality, with some of

5 The year 2017 was, of course, also another significant anniversary year — the 60th anniversary of the Sputnik 1 mission.

6 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies (Outer Space Treaty) 610 UNTS 205.

7 Crowther (1997).

them now part of mainstream space activities.

Another interesting observation is that — again not surprisingly — that book centres around the Outer Space Treaty and the traditional actors involved in space activities. Whilst, of course, both the treaty and the existing space participants will continue to be very significant in the future regulation of space, it is incumbent on us all to take a "holistic" view of how space inter-relates with every aspect of life and what this means in terms of constructing the most appropriate legal and regulatory frameworks going forward.

Indeed, the dream of space, and the desire of humankind to engage with space in more and more ways, has driven the development of space-related technology far more quickly, and in ways that would not have seemed imaginable even a few years ago. And, as typifies much about the development of legal rules in a sphere driven by technological innovation, space law has not, as noted above, kept pace with the multitude of space activities about which we can now marvel, and therefore there might increasingly arise various concerns and uncertainties as to how best address the vast complexities that specific uses of space may give rise to.

Nor, in this author's opinion, *should* law purport to keep pace with this technological change with respect to space, given that the developments are so rapid and fluid. Today's technology is often quite quickly rendered obsolete (or at least insufficient) in tomorrow's world. To assert, therefore, that the legal framework is completely up-to-date in every way is therefore misleading and may even lead to complacency. Conversely, to attempt to provide for every conceivable future development might amount to seeking to regulate for the "unknown," which brings with it another set of inherent risks.[8]

Rather, the most appropriate methodology for addressing these changes is to understand the direction that they are taking and to introduce frameworks with a sufficient degree of flexibility, so as to allow the broader principles to remain applicable to new activities even if the express regulatory provisions for specific "new" space activities are not always comprehensively articulated.

This indeed mirrors the "success" to date of the fundamental principles of space law expressed in the Outer Space Treaty. These remain highly relevant and foundational — perhaps even more so than ever — these five decades later notwithstanding that we are now in a very different space "world." In this author's opinion, those who express the view that the fundamental principles of international space law are somehow outmoded or irrelevant are, in reality, frustrated that they are an "inconvenient" restriction to certain military uses of outer space that violate the essence of the way we are to operate in space. Such views are misguided and demonstrate a lack of understanding of the complex history and geopolitical environment underpinning the development of international space law, as well as the object and purpose of the United Nations space treaties.

The evolution of space activities since the days of Sputnik 1 — and the associated laws and guidelines that regulate those activities — has seen a transformation from an era where, initially, only two States dominated the scene, to one where there are a growing number of space-faring States

8 See Freeland (2017b).

(currently estimated to be around 60–70).[9] This, coupled with the exponential growth of commercial opportunities, has historically seen primarily large and well-funded companies invest heavily in space technology, with a view to reaping significant economic returns.

The beginning of the 1990s saw the commercialization of space really start to expand rapidly. By 1998, the spend on commercial space had caught up to Governmental space expenditure and, whilst both have grown rapidly since then, the commercial sector now significantly exceeds the non-commercial space sector in terms of investment. In overall terms, it has been estimated that the total value of the global commercial space "industry" in 2018 was approximately US$385 billion (representing an annualized growth rate of 7% since 2005), and that this figure is anticipated to grow exponentially to somewhere between US$1–3 trillion by 2040.[10] Whatever the correct upper amount, it is clear that the commercialization of outer space is a powerful factor and a major growth area, rising at a much faster rate than the overall global economy.

The enticement of such significant growth, together with the development of technology that enables and facilitates new and potentially lucrative opportunities in space, appear to be an attractive proposition not only for the established space-related companies, but also for a new breed of space entrepreneurs and smaller (and perhaps nimbler) space entities.

Much has been written about this trend towards the commercialization and privatization of space, and the increasingly important role that non-governmental actors play, not only to serve the needs and demands of civil and commercial end users, but also those of States and even military customers. These trends will, if anything, continue at an increasing scale given the trend towards the "democratization" of space as new actors emerge due to developing technology. This will, undoubtedly, present considerable additional challenges to the overarching 'global commons' legal characterization of space, and the principle of freedom of use of space,[11] that stem from the fundamental roots of space law.[12]

Innovations such as nano/small satellite technology and human aerospace flight will, ultimately, bring "space to more people" in a tangible way: through direct participation and entrepreneurship. This is very important since, perhaps not surprisingly, those involved in the space regulatory "industry" have not "sold" the idea of space, and its significance to the general public, very effectively at all in the past.

As an example, just a few short years ago, this author picked up a copy of the *Wall*

9 Of course, viewed from another perspective, this also means that approximately two-thirds of the world's countries do not have any indigenous space capability whatsoever, placing them at an increasing comparative disadvantage over time and rendering them entirely dependent on others for access to space infrastructure. Obviously, this gives rise to sovereignty and national security concerns for those States.

10 See Higginbotham (2018).

11 Article I of the Outer Space Treaty provides in part as follows: " … Outer space, including the Moon and other celestial bodies, shall be free for exploration and use by all States without discrimination of any kind, on a basis of equality and in accordance with international law, and there shall be free access to all areas of celestial bodies. There shall be freedom of scientific investigation in outer space, including the Moon and other celestial bodies, and States shall facilitate and encourage international cooperation in such investigation."

12 See Freeland (2017c).

Street Journal whilst in Canada and was surprised and initially delighted to see that the front page had an article about space law. He was quickly brought down to Earth, so to speak, by the headline — "If a Martian Wrecks Your Rocket Ship, Who is Liable?"[13] Is this really what people think about the scope and importance of space law? Despite everything that space-related technology can and does do to raise the standard of living for the entirety of global humanity, is this the best that can be said about the laws that make this possible?

It seems quite extraordinary in this day and age that one great challenge for space law has often been is to get people to actually take it seriously. Those of us who have discussed with our respective Governments the need to establish rational, practical and appropriate legal and regulatory frameworks for the development of a viable space industry at the national level have in the past sometimes been met with counter-arguments stemming from inertia and conservatism, financial concerns, differing priorities and, unfortunately, a lack of understanding.

This situation has now changed somewhat — although not universally — and the truth of the matter is that space is, of course, very real and not something to be derided or ignored, but rather a vital element for the very future of our life here on Earth (and perhaps beyond). No country can afford to fall behind its friends and neighbours in relation to important aspects of its space development.

As noted, space impacts on every country and must be embraced in the most appropriate way for each nation, irrespective of its economic, political or industrial circumstances. In short, no longer is space a "luxury" just for the space "haves:" it is now an imperative for all countries and represents an essential part of their vital infrastructure. Appropriate "rules of the road" are therefore necessary and the challenge is to ensure that these provide the best possible way forward in the circumstances of an ever-changing technological environment.

How to address the major legal challenges

In view of this evolving situation, each country is, or should be, asking the same questions: what does the development of space technology mean for us? How can we maximise our ability to take advantage of the use of space for our continuous development? Do existing national laws or policies unduly inhibit or restrict the development of a viable and self-sustaining domestic space "industry," or can they be categorized as "enabling"? What regulatory framework is most appropriate for us in terms of our risk profile, capability, needs, culture, economic circumstances, national security situation and strategic alliances? How can this framework be constructed in a way that is adequately "future proofed" (if indeed this is at all possible)?

The answers for each country will be different, but there is no mistaking the need to address the implications of our ongoing development of space-related technology. They pose great opportunities but their management and regulation — both at the international but, even more significantly, the national levels — raise difficult questions for all decision makers and for the creation of legal frameworks.

13 Hope (2015).

As such, we are standing at the dawn of a new era in space activities, which will require very considerable thought as to exactly *how* to adapt, and adopt, appropriate legal frameworks that are able to strike the most appropriate balance between sometimes competing interests. There is an urgent need to comprehensively assess these challenges and to develop and design the structure and content of these frameworks.

In order to be relevant, innovative and sufficiently "forward-thinking" to properly advance the field of space law, the development of these frameworks to meet the challenges of the 21st century must incorporate a comprehensive approach, breaking down the "silo" mentality that has traditionally characterized not only existing legal research, but also the current space "law-making" and regulatory processes.

In essence, the challenge — indeed the imperative — is to develop legal and regulatory frameworks to properly address the demands and inevitability of technological innovation and an increasingly globalized and connected world, not the other way around.

This represents an enticing opportunity for space lawyers to play an even greater role in the context of the so-called "NewSpace" phenomenon, by engaging more actively with new participants in space and therefore advocating for appropriately balanced enabling laws and legislation to allow for the most progressive path forward. It is not the time for detached and overly academic law-making, rather the future space law regimes must be closely integrated with and aligned to the sheer breadth of influence and impact that space technology does and will assume.

There are other examples of legal challenges ahead for space law. In order to systematically approach these challenges, we must first understand the issues that they give rise to: only then are we in a position to construct, through a cooperative and multidisciplinary approach, the laws and standards that will allow humankind to maximise the benefits to be garnered from the exploration and use of outer space. The position is so fast-moving and fluid, given the speed at which innovation and technology develop, that it is neither possible nor appropriate to any longer attempt to rely *exclusively* on the traditional principles — as important as they will remain — that are to be found in the United Nations space treaties.

Nor can we then rely on a simple "copy/paste" transposition of terrestrial international law principles to somehow fill the gaps in the extra-terrestrial regulation of activities that are clearly beyond the contemplation of the original drafters of the United Nations space treaties. This author has listened with interest to commentators who latch on to article III of the Outer Space Treaty[14] — which provides that activities in outer space shall be carried on in accordance with international law — and who then make a quantum leap to their "eureka" moment, to postulate that laws that were developed on Earth for terrestrial activities can somehow magically fit into the unique environment that is outer space. This is a seductive conclusion, but, in this author's opinion, far too simplistic to adequately

14 Article III of the Outer Space Treaty provides as follows: "States Parties to the Treaty shall carry on activities in the exploration and use of outer space, including the moon and other celestial bodies, in accordance with international law, including the Charter of the United Nations, in the interest of maintaining international peace and security and promoting international co-operation and understanding."

meet the realities. Square pegs do not seamlessly fit into round holes.

With respect to perhaps two of the most pressing challenges for space law — the long-term sustainability of space, and the potential militarization/weaponization of space — the existing terrestrial environmental principles on the one hand,[15] and the laws of armed conflict on the other,[16] whilst relevant, are certainly not adequate or necessarily appropriate in various respects to meet the complexities that these issues present. Both of these pressing questions require specifically crafted legal rules that, even if they do draw on terrestrial law for some inspiration or comparison, are specifically designed to meet the peculiarities that stem from our legal characterization of outer space, as well as the complex non-legal factors that impact and shape the broad range of space activities.

The attempts to deal with these challenges thus far have largely been exploratory, generalized, and on a non-binding and voluntary basis. Whilst much has been made of the importance of "soft law" instruments[17] in shaping the face of the space regulatory regime, this author has reservations as to whether such an approach serves us well in the longer term, particularly in relation to such important issues in the context of our future uses of outer space and, indeed, in many respects, for the future survival of the human race.[18]

Notwithstanding the legal "value" that some such instruments may have, at their core they are merely guidelines or recommendations that do not necessarily have the force of law, unless they are to be regarded as reflecting rules of customary international law, itself a very difficult assertion to substantiate in the absence of, say, a finding to that effect by the International Court of Justice.[19]

Given our increasing reliance on such non-binding measures in a whole range of space-related matters, do we run the risk that they will work only until they don't? Shouldn't they always be regarded only as interim measures, until traditional international law principles can be agreed and applied? And, indeed, is this approach feasible given the multitude of concerns associated with the continued development of space-related weapons technology, and the environmental (and other) risks that they pose?

Ideally, binding treaty norms should be negotiated, to be adhered to in good faith by all relevant States. Of course, in the absence of a change of approach between, in particular, the major space powers, treaty rules are unlikely to come to fruition in respect of these issues in the short and perhaps medium term. Instead, so-called non-binding Transparency and Confidence Building Measures (TCBMs) are articulated as the way forward and are expressed to be stepping-stones towards a more formally binding agreement. The risk is, of course, that

15 See, for example, Boyle (2013); Bohlmann & Freeland (2013); Freeland & Lawler (2011).

16 See, for example, Freeland & Gruttner (2020).

17 Marboe (2012).

18 Freeland (2011).

19 See a whole range of decisions at the International Court of Justice on the issue of how to establish the existence of a rule of customary international law, beginning with the *North Sea Continental Shelf Cases* (Federal Republic of Germany v. Denmark and Federal Republic of Germany v. The Netherlands) (Judgment) [1969] ICJ Rep 3. See also Jakhu, Freeland & Chen (2018).

these binding arrangements never actually eventuate.

This recourse to TCBMs may well represent a realistic assessment with respect to the difficulties in achieving a significant degree of mutual cooperation and the requisite degree of political (good)will to resolve any impasse in a more comprehensive way but, in this author's opinion, in the end, binding norms that also fashion and regulate responsible behaviour by those engaged in space activities will be crucial.

This represents a major challenge ahead for all who understand the role of law in facilitating the peaceful and sustainable uses of outer space in the future. But it is a goal towards which we must all strive: the fact that we do not have such a comprehensive treaty regime in relation to military uses of outer space as yet does not mean it cannot happen. In the meantime, academia, industry and other experts are engaged in research that seek to articulate, at least in the view of those involved, what they perceive to be the *lex lata* rules relating to the military uses of outer space.[20] These are useful exercises although they can never, of course, represent a binding document to which States must comply for fear of be subject to sanctions under the principles of general international law.

Other significant legal challenges

Apart from the two major challenges to space law in the future that have been referred to above, there are a number of other significant issues that will require careful consideration as to their ongoing regulation. This section poses some questions that arise in respect of each of these, each of which will be relevant for future lawmakers and policy designers.

This article has already made reference to the increasing use of small, nano and micro satellites. This technology may represent an important precursor to the establishment of indigenous and independent space programs in States that previously could not have contemplated undertaking such activities. By eliminating some significant barriers to entry, small satellite technology may facilitate capacity building, broader collaborative opportunities, and education/training programs, as well as bridging (some) technology gaps for hitherto non-space faring States. It will also open up even more diverse commercial opportunities for a much broader range of potential service providers.

It is perhaps appropriate to liken the potential of small satellites for space activities to the way that mobile phones have revolutionized terrestrial communications activities. We simply do not know where this technology might ultimately lead and what it will allow us to do. However, we can confidently expect that it will open the door to an even more expansive array of commercial opportunities.

This inevitably represents some significant challenges to space law. For example, what is the impact of this technology for the space "market"? What forms of legal and regulatory frameworks are necessary to balance the interests of a particular State with the demands of entrepreneurs? How will existing space actors react to the potentially new range of participants that this technol-

20 See, for example, the work undertaken in the 3-year project entitled *Manual on International Law Applicable to Military Uses of Outer Space* (MILAMOS), a research project led by McGill University in Canada, and involving experts from 22 countries of the world: available at https://www.mcgill.ca/milamos/ (accessed 30 March 2020).

ogy will allow for? Should the governing legal regime encourage or discourage this evolution towards a multitude of space actors? What role does/should law have in facilitating the commercial possibilities offered by low-cost satellites? How do we deal with the prospect of so-called "mega-constellations" of small satellites, whose (planned) number will quite quickly dwarf the number of space objects launched in the six decades from the time of Sputnik 1?[21]

As noted earlier, there has developed an important cross-fertilization of activities in outer space with those in cyber space. In this regard, it is no surprise that many of the major digital platform companies have now expressed significant interest, and invested large sums of money, towards an incorporation/expansion of their existing operations with additional space activities. This is sometimes referred to as the "GAFTA phenomenon" (**G**oogle, **A**mazon, **F**acebook, **T**witter, **A**pple).

How should the recent interest shown by major digital platform operators be regulated in the space sector? Will there be a major convergence between digital content and the space industry? How can/should law react to, and properly regulate this rush towards the digitization of commercial space?

Another challenge that arises is the development of aerospace technology and the legal regulation of human aerospace and space flight. Much discussion is required about the future legal regulation of these activities and, equally importantly, about who would take responsibility — and how — for the governance structures and legal principles that will be needed.[22] In this regard, one will need to examine the scope and legal/regulatory implications of, for example, proposals to (re)define the areas of air space and outer space into distinct zones corresponding to differing uses of space-related and high-altitude technology (drones, balloons, other high-altitude platforms, air travel, aerospace flights, suborbital flights, orbital flights, space stations, permanent human settlements etc)?

In the area of geo-politics, strategic space, and transparency and confidence building measures (TCBMs), must we really be required to think of space in terms of that now well-worn mantra — that it is "contested, congested and competitive" — or is there another theme(s) towards which future space law should be directed?[23] How can the regulatory framework minimise/mitigate the threat of conflict involving the space ambitions of States? How can we ensure that *all* 'voices' relating to space are heard, not just those that loudly advocate for its designation as a "war fighting domain"? In this author's opinion, such calls are dangerously self-fulfilling and largely self-defeating: all States, particularly the major space-faring ones, will suffer if activities in space are undertaken in such an irresponsible manner as to cross certain "red lines" of accepted behaviour.[24]

And, of course, no overview of the challenges facing space law would be complete without a consideration of the potential for the commercial exploitation of the natural

21 In this regard, one of the major private entities engaged in proposals to launch many hundreds of small satellites has recently announced significant funding problems that will, at least in the short-medium term, most likely curb its activities somewhat; see Amos (2020).

22 See Freeland (2010).

23 See Freeland (2018a).

24 See Freeland (2018b).

resources of outer space. As is well known, the United States Congress passed the Space Resource Exploration and Utilization Act of 2015. Shortly afterwards, Luxembourg enacted its own national legislative framework[25] that encourages and promotes space resource exploitation and utilization. It seems apparent that other States, such as the UAE,[26] may also follow on this path.

These national law developments have highlighted some thorny legal issues but have also brought to the forefront intense geopolitical disagreement at the United Nations discussion level.[27] Even putting those aside, how will technology ultimately enable this commercial exploitation to take place? Is there a potential legal/regulatory model that will adequately support these activities, particularly in light of the uncertainties that some express with respect to the interpretation of the relevant principles of the treaty regime?[28]

These are but a few of the imposing challenges ahead for space law. The existing regulatory regime has largely served us well and, in many respects, has been remarkably successful. But the "spacescape" is changing very quickly, driven by this bewildering technological maelstrom that, over the last five years or so (and certainly for the next period of time), has far surpassed the already rapid evolution in space-related technology that began at the beginning of the space race.

Two important "takeaways:" principles of humanity and stewardship

We thus find ourselves in "interesting times." The need for a more comprehensive and detailed legal/regulatory framework for outer space represents one of the most politicized and complex challenges ahead for our, and future generations. All stakeholders need to work together to find a path forward, in order to meet the challenges. The existing international regulatory framework, whilst important, cannot alone stand up to the complexities that the ever-increasing range of space activities — and the possibilities that still lie before us — impose.

The opportunity presents for Governments, industry, scientists, entrepreneurs and civil society to work together to develop appropriate future legal frameworks that supplement and compliment the robust foundational principles that underpin how space has "worked."

This leads to probably the two most important considerations this author can offer. How should the societal, community and human impacts of our inexorable march into space be measured? Why has there been so little work done so far as regards

25 See https://spaceresources.public.lu/en.html (accessed 30 March 2020).

26 See UAE Space Law Details Announced to Facilitate Space Sector Development, https://spacewatch.global/2020/02/uae-space-law-details-announced-to-facilitate-space-sector-development/ (accessed 2 April 2020).

27 A current (since 2017) item on the agenda of the Legal Sub-Committee (LSC) of the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) is "General exchange of views on potential legal models for activities in exploration, exploitation and utilization of space resources." In addition, in June 2019, UNCOPUOS Member States agreed to convene "scheduled informal discussions" of the exploration, exploitation and utilization of space resources, which were convened for the 2020 LSC session — this has been cancelled due to the current coronavirus situation and most likely will commence in 2021.

28 See, for example, Article II of the Outer Space Treaty, which provides: "Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means."

the human rights aspects of the exploration and use of outer space?[29] What legal and regulatory regimes best protect the broader interests of society without unduly restricting the development of appropriate space activities in the future? And, indeed, what are the criteria by which we are to determine the priorities as to what constitutes "appropriate" future space activities? What role does law play in fashioning these choices?

Furthermore, as we develop frameworks to address these legal challenges, we must always remain cognizant of the "stewardship" role we, as human beings, have in the way we manage our ongoing relationship with space. Our responsibilities in this regard extend not just to ourselves, but to future generations.[30] It is incumbent on us, and imperative for the future of humanity, that we do not repeat some of the mistakes we have made on Earth that threaten our ability to coexist here into the very long term.

In answering these questions, it is important that, at all times, we are conscious of, and adhere to, the core principles of "humanity" that underpin space law, in order to avoid the possibility of scenarios that do not bear contemplation. In the end, the principle of humanity must be the bedrock of all global legal regimes, including the regulation of the exploration and use of outer space.

In this regard, law will therefore continue to play a crucial role. But lawyers certainly cannot do this on their own. They simply do not have the tools to do so. All relevant stakeholders must exchange ideas, knowledge and expertise, and understand how each can contribute to an appropriate future where space continues to play a vital role in the activities of humankind. In the end, these discussions will be the most important way in which all of the exciting innovations and developments that we all dream about can best be advanced.

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29 See Marboe (2013); Freeland & Ram Jakhu (2014).

30 This obligation is already reflected in Article 4(1) of the Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (Moon Agreement) 1363 UNTS 3, to which Australia is a State Party, although it must also be noted that there are currently only 18 States Parties to this instrument, none of which are considered as "major" space powers; see Hobe et al. (2013).

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Military and geopolitical challenges in space

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My[1] duty here today is to talk about the 5% of the time that we think maybe space won't work. It's a pleasure to be here this morning in such esteemed company, but especially can I say welcome to the undergrads in the room. Some of the challenges we're going to talk about today are yours and mine to solve over the next few years.[2]

I have some initial thoughts on where we are in a military and geopolitical context and how we got here, and the direction that some loud voices are moving in. And highlight some of the tools that we might think about as we decide what being a responsible space player looks like for Australia and move forwards in that direction.

So Her Excellency, the Governor, mentioned that space is becoming more militarised. Since the motto of the Royal Society is to question everything, I want to think about that. Is space more militarised? There's certainly more military stuff in space. But there's a lot more of everything in space today then there was 50 years ago. So this quote[3] wouldn't have been out of place in Mike Pence's speech at the International Astronautics Congress (IAC) in 2019, but it's actually a little bit older than that. And Kerrie highlighted some of the roots of different country's space programs and humanity's progress in space, it sort of stems from a lot of strategic competition and from defence purposes. James Doolittle was one of the earliest thinkers on that topic back in 1958. But I think that it's important to consider that that rhetoric wouldn't be out of place today. So I'm not sure if space is more militarised today or if space is just bigger. It has always been a place for strategic competition between nations since Sputnik 1 in 1957. There was an element of strategic competition between the great powers at the time.

As the commercial ecosystem in space has grown, public knowledge around what happens in that domain and what's going on there has grown. I think we are more conscious today of some of the military and geopolitical aspects of the space domain. And strategic competition has upsides. We wouldn't have some of the technologies we have today, like GPS or some of the Earth observation technologies, without those technologies first finding a purpose in defence and strategic competition. If we didn't have Earth observation, we wouldn't have found out about climate change.

1 The following opinions and analysis are my own and do not reflect the official position of the Department of Defence, the University of New South Wales or the Institute for Regional Security.

2 This is an edited version of the transcript of Dr Piggott's talk.

3 "We, the United States of America, can be first. If we do not expend the thought, the effort, and the money required, then another and more progressive nation will. They will dominate space, and they will dominate the world" — James Doolittle, 1958. (James Doolittle led the eponymous Dolittle raid, and subsequently worked in the US space program in its infancy. He was a contemporary of Goddard's and von Braun's.)

A few people have touched on strategy and what it means to be strategic. And what I am going to talk about now is what that looks like for some of the major powers. But first I think it's important to talk about what strategy actually is. Because it's not about winning.[4] It's about attaining continuous advantage, and when we see something like space, which is a limited resource, we often see competition for that resource between different groups of people. So it's important to remember that we're not talking about a particular end state, we're talking about planning for continuous advantage. What does that mean to a few different countries?

We have heard some rhetoric that most of you will be familiar with from the Vice President of the United States at the IAC. I think that what Space Command said is sort of a little bit more moderate in terms of their outlook,[5] but there's a range of opinions in the United States, from an America First sort of point of view to a more moderate point of view that recognises the importance of space to all of those national enterprises, to a realm for competition between the United States and other great powers. So I think that quote's really powerful in being a 2019 version of what General Doolittle was talking about back in the '50s.

The idea of space force is not as new as Donald Trump. That idea has its genesis in some law-makers in the United States before he appeared from some people who were unhappy with how the US Air Force managed space capability development. Mike Pence has directed NASA to return to the Moon by 2024 and some of the people that I've spoken to in NASA see that timeframe as a bit challenging. To wrap all that together at IAC we saw a real tension between different parts of the American leadership between what American dominance looks like and what role there is for international partners in the role for the United States and space. Jim Bridenstine, the NASA Administrator, spoke about the importance of international partnerships. So there's a real lesson there about — that's peculiar to the United States in terms of what people at the working level think about international collaboration.

Russia's another country that's reorganised its defence apparatus to better leverage the space domain. There are a couple of quotes from Russian Military doctrine, that's a little bit long in the tooth now and some more recent comments from the Defence Minister.[6] So they've gone the opposite direction from a space force. They've wrapped some of their space elements up with some other air defence assets because they see some synergies there that are going to help them better secure space for Russia. I think it's important to highlight that the Russian Military sees warfare as a contest for information over a number of domains without often clear boundaries, which is a little bit different from speaking about space as a war fighting domain. So there are some differences in approach between

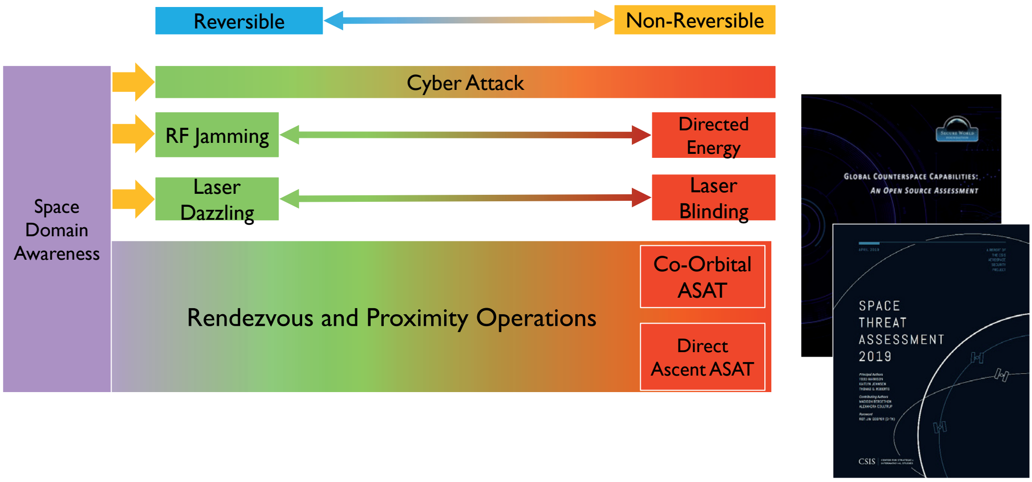
4 "Strategy is not about winning … Strategy, in its simplest form, is a plan for attaining continuing advantage" — Everett Dolman, 2004.

5 "The U.S. must recognize that space will be a major engine of national political, economic, and military power for whichever nations best organize and operate to exploit that potential." — USAF Space Command, 2019.

6 "The securing of supremacy on land, at sea, and in the air and outer space will become decisive factors in achieving objectives" — Russian Military Doctrine, 2010. And "[There has been a] shift in the combat centre of gravity towards the aerospace theatre" — Sergei Shoigu (Russian Defence Minister), 2015.

Russia and the United States, and you can see how they're organising for best effect.

When we talk about whether space force is a good thing, whether it's ethical, what the implications are there, I think it's important to remember that there are other ways of organising that are maybe not so bombastic, that we need to give equal consideration to.



Finally, China. Chinese strategic writing emphasises that space is essential to operating in the other domains, and the same report from US Air Force Space Command is explicit about calling out China and their long-term strategy for displacing the United States.[7] The Chinese Academy of Military Sciences talks about fighting a quick war as one of the characteristics of space operations and they see that as essential to their ability to deter their adversaries geopolitically.[8] The People's Liberation Army, of course, has organised a strategic support force that wraps up space, cyber and electronic warfare capabilities in the People's Liberation Army. So it's a third, different again example of a Military space organisation.

So I will leave you with Figure 1 where I'm going to talk about some of the actual tools and systems that give Steven and me pause when we think about what people can do in space. Space domain awareness on the left-hand side does what it says on the tin, that's understanding what's happening in space, where spacecraft are, what they're doing. Without that, you can't achieve any of those other effects if space turns into a war-fighting domain, that you can see over on the right-hand side. So the first thing I want to talk about is cyberattacks. I'm not a cyber expert, but I don't think it's news to anyone that spacecraft and ground stations are vulnerable to cyber effects. The second thing is a sort of spectrum from radio frequency jamming to directed energy weapons. We see in the public domain that the Defence Intelligence Agency commented this year on some Chinese satellite communication jammers over a range of fre-

7 "China is executing a long-term strategy with the explicit aim of displacing the U.S. as the leading space power" — USAF Space Command, 2019.

8 "Whoever controls space controls the Earth" — China's Academy of Military Sciences, 2013.

quency bands. And it won't be news to any of you that those are frequency bands that are pretty commonly used across the military and civilian sectors. We also see from the Defence Intelligence Agency that GPS jammers have been deployed in the Spratly Islands and the Chinese have published scientific papers on laser blinding techniques and successfully did that against one of their own satellites in 2013.

That brings me to my second point. There's another spectrum there between laser dazzling and laser blinding. We're talking about a spectrum from reversible to non-reversible effects here. So the same laser that you can use at a lower power setting to dazzle a satellite, you can amp up the power and burn out the charge-coupled device (CCD) camera.

Finally I want to talk about rendezvous-and-proximity operations. That bleeds into space domain awareness because all three of those countries have demonstrated rendezvous-and-proximity operations programs. That's about driving satellites around in orbit to go and check out other satellites and see what they're doing. There are a number of applications for that from intelligence to verifying arms control treaties, to removing debris in space. Having that capability is essential to all of those things, and not all of those are military purposes.

The two final points on Figure are about co-orbital anti-satellite weapons and direct-ascent anti-satellite weapons. If you can do rendezvous and proximity operations, there's no reason you can't put bombs on satellites and drive them around in orbit.

And we've seen direct-ascent, anti-satellite (ASAT) tests from, most recently, India, but also China, Russia and the United States. And if anyone's looking for more information on any of those things, two reports from the Center for Strategic and Independent Studies[9] and our friends at the Secure World Foundation are excellent resources to get more awareness about that.

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Ethical challenges in space: norms and conventions for peaceful spacefaring

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Members of the Society and the Academies, distinguished guests, it's an absolute honour to be here today to talk to some fantastically curious minds.[1] This is the speed-dating version of space ethics. These are my opinions and not the opinions of the particular organisations that I work for. In 2020, I will be the Senior Ethicist for the Air Force with a mandate to work in space ethics and even then my opinions will be my own as well.

What is space ethics? I had a lovely experience with a 14-year-old girl: I go and do a lot STEM things — people were talking earlier about how we do training. I'd like to say all of us in this room have a responsibility to get young people excited about science and space: I go into high schools and I talk about the ethics of what they're looking at, and get young people to talk about those sorts of things. My favourite story is of a 14-year-old girl who, when the teacher introduced me, said, "Oh you're a space ethicist, is that like a real job?" I'd just like to say when the Governor today mentioned space ethics, I was sitting up the back going, "It's a real job."

What is space ethics? Obviously space ethics is looking at the ethical implications of what we do in space and also within the space industry potentially on Earth and potentially about the future plans that we have. Realistically it is ensuring that what we do in space is not just legal but is also ethical. It'd be great if it could be both. It's also important that we look at what is ethical, not just for now, but for future generations. When we were talking about going to Mars earlier, I was really excited because there's actually a conference in Adelaide in a couple of weeks' time looking at radiological protection and going to Mars. They've got me coming in to talk about the ethical implications around some of those things. For example, around genetic changes that might happen to people in space. So it's about our future generations as well.

A second example, which has been discussed today, is space debris. I'm sure you are all concerned about climate change and the problems that are associated with that on Earth. It's an awful situation that we actually need to work on now. That keeps many people in the world up at night. You should also be awake worrying about space debris, let me tell you. Much of our lives revolve around the use of satellites, particularly in low-Earth orbit. One of the concerns around space debris is that we will get to something called the Kessler syndrome which is a cascade effect of many different accidents (or potentially formed on purpose) and there is a concern that it might actually make an entire area of Earth not able to be used. The idea of Elon Musk putting 40,000 CubeSats up keeps me awake at night.

1 This is an edited version of the transcript of Dr Coleman's talk.

One of the other areas that we've talked about today is Earth observation. It was great to hear of Planet [?]: they do some really interesting work. They actually map the work, take photos of the Earth every 24 hours and they make those images available to humanitarian groups, for example, who can track when refugees are being moved or when there's problems with particular crops, for example. They do a wonderful job. But they are in the process of making money and I once asked them some really awkward questions such as, "Will you sell your data to anyone?" And they were, like, "Well, we've got to make money, of course we'll sell it to anyone". I'm, like, "Okay, let me put the ethicist hat on for a moment. Would you sell it to a rogue nation who wants to invade Australia?" and they were, like, "Oh, well, you know, we'd have to think about that." Okay. "Would you sell it to the drug cartels who want to try and work out from looking at mapping data about how their competition is actually moving drugs around in another area?" One of the concerns that I have is that we talk about space being available for all, and that's actually a really noble aim, but there are some groups that we actually don't want to have easy access to space and potentially use space in a nefarious way against us and potentially against future generation as well.

Which leads me to my next point. A lot of my research is on space terrorism, and, let me tell you, I would not recommend this as an area of research to go into because every time I fly to America, I am randomly selected when I go through the security line. I would not recommend it. But, I and my team have looked at — spent far too much time looking at — how nefarious groups whether they be non-state groups such as ISIS or rogue nations, who could actually use space against us. We rely on space for so much of our lives: for communication, for navigation, for financial markets, for food distribution systems. If those things went, if we lost low-Earth orbit and we lost the use of those satellites, then our lives would go back to the 1950s, and a lot of you might remember that better than me, but it actually would have a huge impact on a very large number of vulnerable people in society. And it raises other bigger issues, ethical questions regarding space. For example, it's been wonderful that we've actually talked about the indigenous use of space, but there's not a lot of discussion being had, apart from Alice Gorman, about the impact on indigenous communities on the use of space all around the world. Because often these space launch facilities are put in locations that actually kick indigenous people off their land, who take away their livelihood — there's been a long history of this.

It's really great, however, to see two very positive, ethical space stories. The two that I'd just like to highlight with you are Rocket Labs in New Zealand and Equatorial Launch in Australia. Both of those groups have actually looked very carefully at the impact that they could potentially have on indigenous people. And it's just not a tick-a-box, "Oh yes, we've talked to the local people", they are actually working on meaningful, long-term partnerships so that each group is learning from each other.

There are many wonderful uses of space, some of which we've heard about today. For example, going back to the Moon and going onto Mars. Or constellations of small CubeSats that could actually bring the internet to large groups of people, for example, in India and Africa, similar to the Google

Zoom Project. There are many wonderful ways in which space can be used, but I think all of us have a responsibility — to the present, to future generations and also to our planet — to actually ask the ethical questions about how this could potentially be used in a more nefarious way or have unintended consequences. Because sometimes those unintended consequences, such as the Americans giving blankets to the indigenous people, can wipe out an entire group of people. And we have to think carefully about how we utilise the resources that we've got.

Thankfully we have some really great people working on this. You'll be pleased to know that Australia is one of the leaders in space ethics, and in the area of military space ethics we are actually the world leaders, which is really encouraging.

Lastly, one of the things that concerns me — and I have to be guilty and say I've used the "wild west" phrase before and I need to make sure I don't say it anymore — is that space is becoming increasingly congested, contested and competitive. Right now we need strong laws and we need a strong body to be able to enforce laws that relate to space operations in low-Earth orbit, all the way up to asteroid mining. There are huge ramifications if we get this wrong. Just recently an Israeli company put something on the Moon, accidentally crashed it into the Moon, but it actually contained organisms, organisms in amber, organisms called water bears (or tardigrades), which can actually survive in these sorts of environments. The Israelis hadn't told anybody that this was on their payload. They added it as a secondary payload to another launch. So my concern is that we have laws, but we need to ensure they're actually enforced. Not just so that we can have red tape and bureaucracy and give bureaucrats jobs, but so that we actually make the environment here on Earth and in space safer for now and also for future generations.

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The promise and peril of space: viewing space through the media

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I'd also like to acknowledge that we're on Gadigal country. When you work in the business of science storytelling, science is pretty broad. There's a lot to cover. But there are a couple of topic areas that feel like big-ticket items, that seem to have really broad appeal and to cut through with a wide variety of people. One of them is dinosaurs, and the other one is space.[1]

We're going to leave dinosaurs to one side today and I would like to try and ask what it is that makes space so appealing for people, from my perspective of our audience, looking at a couple of the stories that have cut through and why, based on some of the coverage and content making that I've seen happen at the ABC in the last year or so. The three kind of themes that I think are part of that appeal are, first, *mystery and danger*; second, the thrill of *exploration*; and, third, flat-out, good old *wonder*.

Mystery and danger

Starting with mystery and with danger, it doesn't get much more mysterious than black holes. I'd be very surprised if you haven't already seen the picture, of a black hole (Figure 1), because it was pretty inescapable at the end of April, 2019, when it was revealed by the Event Horizon Telescope. It was our first actual image of the Event Horizon of a black hole. I actually covered the Event Horizon Telescope back in 2015 for the BBC and they said then that the picture would be out in 2017, so it was another two years after that. We knew it was coming, but it was 11:30 p.m. when the story actually broke. I was in the newsroom helping to get it up on the website and go home. It actually broke just before midnight, got about 50,000 views even before midnight and then next day's news agenda got a bit of a shake-up. But the next morning Scott Morrison called the election.

Figure 1

Our news site published eight or nine different stories about the election that Thursday, we did two stories on the black hole, unusual for a science story. We're not normally called upon to do a follow up, we just do one and get it out there. You can guess who won in the page views. Nine or ten stories about the election, two about this iconic brand new image of a black hole and that's where

1 This is an edited version of the transcript of Dr Webb's talk.

all the attention was, it wasn't even a contest. And it wasn't a slow news day either. Julian Assange was arrested that day and Geoffrey Rush won his defamation court case as well. Sorry Julian, sorry Geoffrey, you were third and fourth place respectively. I think that speaks to something because there is not really a more mysterious frontier than the Event Horizon and suddenly we were looking at it and no one could look anywhere else. In fact one of my colleagues on the news desk, Riley, observed that it was pretty obvious looking at the results from the website, that Australians would rather stare into the void than think about another Federal election.

There's also a bit of a sense from black holes of danger. We all know that if you fall across that horizon, you're not coming back, and there is this sense of peril as well,. Another aspect of the appeal of space actually usually plays out through a different type of story: the often feared and discussed asteroid impact, usually illustrated with varying degrees of verisimilitude.

I don't know if anyone saw an asteroid story in the *Daily Express* recently, I don't even know what's going on in that one. I might need an asteroid physicist to explain to me if that's even possible. But there's definitely an appeal or an attraction, a hook in that sense of danger. And in fact, arguably I would think there's something to that, it's not unreasonable. Because even when you present stories about asteroid impacts in a fairly reasonable, sensible straightforward manner they really do connect. We did a three-part series on science fiction, our program and podcast at ABC Radio National, earlier in 2019. There were three different types of apocalypse but it was the second, about the possibility of an asteroid impact, that really seemed to connect with people the most. So people are genuinely, and I think justifiably, intrigued by this idea of space rocks that may be out there and do occasionally come quite close by and what are we going to do about them. And the podcast interviewed someone whose actual job title is Planetary Defence Officer at NASA, who talked about the fact that there are not enough eyes on the sky in the Southern Hemisphere, and so there's a bit of a blind spot in terms of asteroids coming at us.

Exploration

Apart from mystery and danger, there's a very different type of engagement as well, which is a bit more relevant to some of the other themes of the Forum, and that's of exploration. In 2019 there was the anniversary of the Apollo 11 landing and everyone generated content about the first Moon landing. Program stories, the works, but actually nothing that we did, at least in my unit, got quite as much traction as the black hole image. I think everyone knew what was happening because it was on every single outlet and website and so on, but I think it's the newer frontiers that make people even more excited and they were really interested in the Apollo landings. But there was no single piece of content that totally blew everyone away because I guess we were retelling the story for people like me who weren't alive when it happened. I loved it. I got to feel really up close to those events for the first time.

When we start crossing those frontiers again, going back to the Moon and the first time anyone sets foot on Mars, that will be an unmissable story that will blow whatever election is being called that day completely out of the water.

But the other aspect of the thrill of exploration or even engaging with space that I think really gets people's attention — apart from the progress, the boot prints on the Moon — is the actual mechanics. The practical aspects of how we do it, because the scale is not like anything else that we really try to do. This is a story I've wanted to tell for a really long time: I got to ride on a ridiculous piece of equipment, which is the Stratospheric Observatory for Infrared Astronomy. It's a telescope on a plane that NASA was planning and building for a long time. They now run it together with the German space agency, DLR, and it does astronomy at about 40,000 feet through an open door. It was a real privilege to tell that story and I wrote up their observation of an occultation, a particular type of eclipse, and people loved it. We got comments that that radio program was half an hour of radio that felt like five minutes. We got people writing in saying, "That's the best news story I've ever read on the ABC website," and I was pretty pleased with the job that we've done of it, but the credit I don't think belongs to me. Because what they were engaging with was the fact that NASA has a telescope on a plane and they use it to chase shadows, which is ridiculous. I think those mind-boggling aspects of the actual technology and the mechanics of the way that we either explore or do science about space are actually a significant hook for people.

Wonder

Finally, though, I mentioned above that just old-fashioned, flat-out wonder is another really important, appealing thing about space that we shouldn't forget. Several months of daily web traffic to all of the science content that my team puts up on the website at the ABC through 2018 show there are some days that are a bit higher than others where we put out more stories or whatever, but there's one big spike, sort of towers over the others, and we only put one story up that day. Can anyone remember what happened towards the end of July in 2018? There was an eclipse. No new findings. It wasn't the black hole image (which was also a very big spike along those lines), but this was actually the longest lunar eclipse that we'll get this century. And earlier in the year we had changed stat systems so I can't put it in the same graph. There was another spike that was even bigger and that was for when we actually had two eclipses in the same year; most of that traffic comes from search. It comes from people typing into Google the fact that there's an eclipse happening and they want to know where it is, how they can see it and what's going on.

These are big events for people, and it's news to me as someone who thinks of himself as a hard-nosed news journalist by training, used to getting a bit sniffy about eclipses because they happen all the time and they're not that interesting for scientists. But people really do care about them, and look for them online, and if we can give them the information that they need, it works for us.

Another thing I thought was going to be a little bit naff was when we worked with Brad Tucker at the ANU to do a big stunt during a live star-gazing TV show, where we hoped to get as many people as possible all looking at the sky at once. Sure enough, despite my reservations, we smashed the world record and people turned out in their thousands to just get a telescope out and they weren't looking at an unusual event, they were just looking at the Moon. But we had more people looking at the same object than had ever happened before, as clocked by the Guinness Book of Records. There's something about that straightforward sense of wonder that you can also share with people because people were doing this with their families and their kids, and that really, really resonates. So old fashioned wonder that you can share, I think, is an important thing not to neglect.

Finally, we tried to sum up that sense of wonder, where you feel small and kind of dizzy just from the scale of the universe compared to yourself. We called it Cosmic Vertigo and we created a podcast of the same name which tries to tap into that sense of wonder, and we got possibly my favourite piece of feedback that we've ever received in the science unit from someone who had listened to this and was moved enough to write in. What Matthew said was this, "Thank you very much for the great work. I've just gone and bought a telescope and I'm going to use it to look at the stars with my son, who's currently so small that all he can do is chew on the handles." That speaks to that straightforward sense of wonder and the ability to share that we get from the sheer scale of space. I'll finish by referring back. I heard Annie say that space is there for humanity, but I think part of the really popular appeal of space is this sense of complete kind of Cosmic Vertigo, as we dubbed it, which is actually that, from the perspective of space, humanity is something of an afterthought.

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Space heritage: artefacts and archæology

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One of my favourite topics in the world is archæology and how it intersects with space industry and space exploration. I'm going to start with the basics on this topic: what is space archæology?[1]

People tend to think archæology is the study of the past, usually the deep past, far beyond living memory and they associate it with the cultures of ancient Greece, Rome, Egypt, et cetera. And the Australian public has come, finally I think, to understand that we have a very deep archaeological record in this country as well. It's very different to the northern hemisphere, but changing paradigms about how human societies work in its own way.

Sure, there's a lot of archæology which is actually about old stuff, but the actual definition of archaeology is the study of how humans relate to material things. Whether that's objects or artefacts or the environment or architecture. So it's actually a set of theories and methods which examine how humans operate in the material world through those very physical objects.

For this reason, it is not confined to the past: it can be applied to the present and even into the future. When we talk about space archæology, we're looking at a very particular where, what, why, who, when. And the what is all of those objects and places that are associated with the human movement into space, generally after the Second World War.

When? If we wanted to put a beginning point on the space age, it really begins around 1936 when the first rocket truly capable of reaching orbit was developed: the V2 rocket, which was actually a weapon of war. Our time period is 1936 up to the present. Where? In terms of geographic range, if you like, we're looking at stuff on the surface of the Earth, right throughout the Solar System, and beyond the Solar System where the Voyager 1 and 2 spacecraft are currently fleeing through interstellar space. Incidentally, there are only 17 V2 rockets left in the world; two of those are here in Australia at the War Memorial in Canberra.

So this is what space archæology is and I often also get asked, why does this have to be archæology? Why isn't it just history? Don't we have an extensive documentary record of everything that went on in the space age? Usually archæology is the techniques you go to when you don't have any written record. Well, it's true, we have this incredible record of documents and letters and plans and images, but like all documentary records, there are huge gaps and sometimes the only way you can find out about something is to go to that place or to find that physical object.

So there is a reason to make this archæology and no just history, but there are new and different things we can learn from an archæological approach, and given how

1 This is an edited version of the transcript of Dr Gorman's talk.

much the contemporary world relies on space, I think it's important that we use any means available to try and understand what is this world we're currently living in, in which technology and all of the social and political changes which come with that are moving incredibly fast. To contextualise these changes within a deeper context of human history and human technology and material culture is important and I think we can learn things about the way forward by looking at the archæology. So that's the archæology, but there's another aspect to this which is heritage, which is basically stuff from the past that people in the present think is important and want to keep for future generations.

These are the same physical objects. A large part of my research has been focused on space debris in Earth orbit: in effect a cloud clustering around the Earth in lower-earth orbit and a broad ring around the Earth, which is the geostationary orbit where most of the telecommunication satellites are. Space junk is a problem. What we have at the moment is more than 35,000 objects larger than 10 centimetres, and millions and millions and millions of objects below that size, down to really tiny micron, submicron dust particles. All orbiting at incredibly high speeds providing a threat to functioning spacecraft. It's a problem that needs to be solved and many people are tackling this problem from a number of different angles.

My angle on this is informed by my previous career as an archæologist working in heritage management with Aboriginal communities in Australia. For me, environmental management very much included consideration of the social significance of objects and places that were important to people. I was working in a context where heritage was an accepted part of general environmental management. And this is the approach I've been taking to space debris in Earth orbit as well. Just to give you a very quick flavour of this, among the stuff in orbit classified as debris is Australis-OSCAR 5, a satellite created by a group of students at Melbourne University, launched in 1970 and still in orbit.[2] This is a piece of Australia's space heritage: one of only two satellites, not counting a bunch of CubeSats that were launched in the last couple of years. It's classed as junk but, I would argue, we don't want someone to zap it out of the sky with a laser or collect it in a debris-collecting space tugboat whenever we have that technology, which isn't happening anytime soon. We want to keep it in orbit. It's evidence of Australian engagement with space. It's evidence of successful space technology driven by the precursors of our current CubeSat revolution. People who made a little satellite on a low budget and had tremendous scientific success for it. I think this is a tremendously important object.

Finally, I'm going to leave you with a thought: we have seen the first launches of Space X's styling satellite constellation. This is going to number in its thousands over the next few years, and there are other companies proposing to launch similar numbers of satellites as well. It's going to radically change the debris environment. It's also going to radically change human perceptions of the night sky. Satellites and space debris are going to be more visible to us than they have ever been in the past, and within a few decades there is going to be no

2 See a photo of the satellite, Figure 5 in Dougherty, above.

one left alive on Earth who has had a view of the night sky before there were human objects in it. This will be the only night sky humans will ever have known. And that is the end.

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The privatisation of space: does NewSpace create companies or cults?

Ceridwen Dovey

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For a few years now, ever since meeting the pioneering Australian space archaeologist, Alice Gorman, I've been interested in social and environmental justice in space activities. Lately, in response to any call for more ethical accountability when it comes to what humans do next in space, many mainstream space enthusiasts or industrialists say the same thing: *you're dreaming*. Those among us who are asking for an ethics of space use and exploration that is as complex and considered as humankind deserves are being written off as naïve, idealistic, irrational.

As a social anthropologist by training, I know enough about human history to understand that ethics almost always loses out to economics, though I still fervently hope one day that might change. Yet I think it's also important to point out that most of the grand *commercial* plans for space are in fact themselves naïve, irrational, emotional, fuelled by cosmological visions and private fantasies, and underpinned by myths. There are a bunch of megalomaniacal Captain Ahabs out there right now, chasing the elusive white whale of conquering space (and we all know how that ended for the troubled antihero of *Moby-Dick*).

I think the playing field might become more level once we can accept that this is not about NewSpace rational economics versus a warm-and-fuzzy delusion that we could peacefully and equitably share the global commons of space. *Any* proposal for what we do next in space, at this moment in time, is equally nutty, speculative, aspirational. This is a liberating realisation, because it means no single narrative of a human future in space has yet become dominant, set in stone. It means that we still have time to understand that we are responsible for what we imagine — whether we dream it up in a science-fiction novel, or on the rocket-factory floor, or in the boardroom of a start-up incubator.

It means that we still have time to acknowledge what we have long known, and ignore at our peril: that ethics and justice do not sit *outside* of other human activities like science and economics. The theoretical physicist and feminist Karen Barad was one of the first to make the point that "ethics … is being done right at the lab bench," and that it's far too late to start thinking through the "ethical, social and legal implications of various new sciences and technologies after the fact."[1]

Let's consider some of the generalised irrationalities of the most powerful NewSpace companies. I don't need to mention them by name. You would know who I'm talking about, and their values trickle down within the NewSpace industry so that there's an element of their approach and worldview in even the smallest space start-ups.

1 Barad (2012).

Firstly, these companies are usually led by a charismatic, wealthy white man, who believes that he is single-handedly responsible for saving humanity by creating a backup civilization somewhere else. These leaders like to speak breathlessly of the spiritual value of gazing at Earth from space — the so-called "Overview Effect" — saying it will make us better people; while at the same time, they actively recruit the global 1% to buy into their company's promises for the future, a future built on inequality in space as on Earth.

The leaders pour their own fortunes into their companies, diminishing their personal wealth in the process, like in a traditional potlatch ceremony, or cargo cult, where destruction of one's own material wealth is the first requirement of being allowed to join, and is in fact a demonstration of one's social prestige. They have even been known to make sacrificial offerings, like sending their own cherry-red Teslas into space. Secrecy and suspicion of outsiders is paramount: nothing is transparent; everything is done in "stealth mode." There's no outside consultation — even of the space science community — before hugely consequential actions, like releasing vast constellations of small satellites into low-Earth orbit, or deciding at the very last moment (and in complete secrecy) to stick some dehydrated tardigrades to a time capsule being sent to the Moon. The leaders may even ask their followers to agree to a suicide pact to prove their commitment to the cause, like a one-way trip to Mars.

Is it just me, or does all this sound a lot more like the workings of a cult than a company?

Even more cultish is the way that investors are hoodwinked into buying into a fantasy rather than actually expecting a sensible return on investment. David Valentine, an American anthropologist, has been doing fieldwork for years in the American NewSpace industry. When you invest in NewSpace, Valentine writes, you are *not* expecting the usual return on investment — since there is no real exit strategy for investors as there would be on any other investment in a frontier economy. Instead, part of the return on investment they are promised is in the currency of intangibles.[2] On the angel investor Space Angels website, for example, is the company's motto: "Explore-Invest-Ascend," and a promise that space investing offers access to "adventure," "meaning," and "that lost sense of wonder."[3]

This is not capitalism as usual. These are not rational economic actors. This is irrational investing. These companies, Valentine writes, are not only built around a profit motive. They have a cosmological, ideological underpinning. The U.S. Space Frontier Foundation, which coined the term "NewSpace,"[4] admiringly describes the NewSpace industry as the "Vanguard of Human Civilization."[5]

So: these companies are in fact not just exporting neoliberal capitalism to outer space. That would give them credit, at least, for being rational actors. What they are doing is, to me, much more chilling. They operate more like fledgling libertarian cults, sending missionaries who've drunk the Kool-Aid out to places they probably should not go.

2 Valentine (2012)

3 www.SpaceAngels.com (accessed 10 November 2019)

4 Valentine (*ibid*, 1053)

5 Valentine (*ibid*, 1060)

It's one thing to criticise these companies for wanting to turn a profit in space — with all the possible destructive and conflict-causing outcomes this may have. Yet, increasingly, I think that is missing the point. We should demand absolute transparency and regulated accountability from all NewSpace companies and their founders because they are planning to build new worlds from scratch out there, supposedly on our behalf. I don't know about you, but I find that super creepy.

Space is hard, right? We're told that all the time, but it's almost always meant in relation to the technicalities of getting there. Why do we embrace those technical challenges but find ourselves so often stumped by the other interesting challenges posed by space — the ethical, moral, philosophical, ideological ones? If we want to be our best selves out there — a dubious myth promoted by many with space ambitions — we should all feel empowered to question the cultishness of the NewSpace vision, and if they really are *doing it for us*, they shouldn't feel threatened by our questions and criticisms but should welcome them. If space is going to be the canvas on which we paint our greatest masterpieces as a species, we all should have a say of some kind in what our human future there looks like.

For further reading, see Dovey (2018 and 2019).

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Transformation of the global space industry in the 21st century and the NSW rôle in space

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There are three phases of space development: exploration, experimentation, and exploitation.[1]

The *exploration* phase is characterised by a journey into the unknown. It's usually high risk and inevitably high cost. And because of that, it's usually driven by government agendas, hence it's generally funded almost exclusively by governments. This was the case for the start of the space race and entry into space. From a commercial perspective the business paradigm is pretty much that industry has a role as an equipment or service provider to meet those government agendas. When you go to the next phase, the experimentation phase, not a lot has changed.

The *experimentation* phase builds on the successes and applications identified in the exploration phase. Again, it's usually high cost but it's lower risk because you do know something about this new environment and how to operate there. You've been there, you've learned from those experiences. This phase is usually focused on the understanding of the new environment and developing a means of operating. Again, it's usually driven by government agendas. Often these are military. They can be economic and, in some cases, prestige. Again, as a result of that, it is usually funded directly by governments. And the industry paradigm is similar to the first exploration phase: industry is mainly a supplier to the government to meet the government agendas. But it begins to selectively invest or explore commercial opportunities.

The third phase, the *exploitation* phase, however, sees a rapid change, almost an inversion of what has happened in the earlier phases. This phase is characterised by the technology and the science of the new medium being fairly well understood. There is usually a demonstrated value of operating in the new medium and often unique services are possible. The cost might still be high but substantial commercial returns become a possibility. Risk can be mitigated in different ways, managed in slightly different ways. First, you know the medium a little bit better. But, second, insurance can sometimes become available to insure commercial missions. In this environment industry begins to leverage off the government infrastructure or selectively look to build its own where it can return a profit. The business paradigm here flips dramatically. Industry begins to actively invest, in addition to government. Market forces then begin to drive investment and commercial activities start to outpace policy and the legal and the regulatory issues, which can lead to concerns that we should think about. But for this discussion at the moment I'm

1 This is an edited version of the transcript of Dr Barrett's talk.

going to focus on what has been happening in space to this date.

What happened to the space environment, the space regime, when space entered the exploitation phase? What happened to global space revenue from 1973 to 2017? In my view, the end of the exploration phase was pretty much the end of the Apollo missions, roughly around 1973. The total size of the space economy was US$15 billion at that point. $12 billion of that was the government payment to companies to build stuff for them to go into space. And there was a nascent emerging telecommunications industry that was generating about $3 billion. 1998 marked a real watershed in the space industry because that's the year that government expenditure on space — what was generated by governments paying companies to build stuff for them — was matched by what was earned by the commercial sector in its own right. The total pie at that stage was $68.8 billion, split half and half between commercially generated returns from space and the government programs that were actually buying services from companies in space.

What has happened since the turn of the 21st century? Commercial space has skyrocketed, as it were. The total pie in 2017 was US$383 billion. Government expenditurn has continued to rise: in fact, government expenditure over the entire period, from '73 to 2017, had a compound annual growth rate (CAGR) of around 3.5 to 3.8%, nothing to sneeze at. But CAGR for the commercial sector alone since the turn of the century has been 11.6%. Such a rate of return over a sustained period of 20 years is incredibly significant. In that timeframe, very few other endeavours have achieved this — the Chinese economy grew at about 13% CAGR over that same period. This is why the venture capitalists, the companies and countries are saying, "We need to get into commercial space. There's money to be made there." The CAGR through 1998 of the entire space economy was 6.3%.

Commercial activities now comprise 80% of the space economy. The biggest transformation that has generated that is the move to the consumer market. Many of the many revenue streams did not really exist 20 years ago. Satellite direct-to-home television comprised the largest chunk of the commercial revenue then (25%). It was only just starting to come in place in the late '80s, early '90s, but has skyrocketed since. The global navigation satellite system (GNSS) and services derived from that make up the next biggest chunk of that, nearly 36% of the industry, including: the equipment used to receive, sat nav implements in the cars, the things that you have in your cell phone that are doing the tracking. All of that is part of the GNSS industry and the services derived from that. And there are others — satellite broadband (8%) has now increased and we now have that here in Australia. And satellite radio (1%), which is still largely based in the United States.

So when you look at what's been taking place in the last 20 years globally, how has Australia performed? Well, it turns out that in space Australia is mirroring what is going on elsewhere. Many people don't realise that Australia has had an extremely strong heritage in space. But we haven't been really good at publicising it: it's usually been people in the know who understand it. One of the things that we in the Space Industry Association have been trying to do is to raise that profile with people like yourselves and others in the community, that actually Australia does have skin in the game and we do have capabilities and we can move forward. Some of our reports show that there are over 600 organisations in Australia that are involved in some way in space activities. The Australian space sector actually generates annual revenues of around $4 billion per annum from space products and services. (The ERG report[2] did a more fine-tuned look at that and came up with $3.94 billion.) So we're in that range and this is what the government intends to grow over the next ten years, up until 2030, to triple that $12 billion per annum.

The Australian space industry has around 10,000 staff who are employed in an activity which, at some point, requires them to deal with space in some way. Not everybody is full-time in space of those 10,000 but it's an important part of what they have to do. They are spread across all six states and the two territories in Australia. One of the really interesting findings is this: we looked at every industry sector that the Australian Bureau of Statistics (ABS) uses to categorise Australian industry, to identify which sectors use space services in some way in the normal day-to-day running of their businesses. We expected to find a lot of that, but we did not expect to see that every single sector was included. If you look at the way that is spread around the industry — we chose to use nine ABS categories to describe the activity — it's the satellite systems, it's the things that go into space. It's the launch system, what takes them there. It's the ground networks, which control space activities or communicate with space activities. It's the space-enabled services which are the downstream products of space, including your satellite communication, your position navigation and timing, your earth observation. Then it's the support services, which include legal, regulatory, as well as specific engineering support. It's space-related R and D. It's space-related learning, education and learning. It's the other categories of media, museums etc, public outreach. So you can see that, like the rest of the world, Australia has most of that in the space-enabled services side. We're very strong in ground stations. And we have very strong in R and D and space education and training.

Looking at the ABS statistics of which industries use space: the Federal Government, Defence, the science community. But agriculture, fisheries, forestry and mining are also big users of space. And every state and territory has space staff. New South Wales is the engine of space growth in this country. More staff are here, more revenue here, and that's largely due to the satellite telecommunications industry.

Australia has a very vibrant innovation and start-up scene in space. There are over 50 start-up space companies in Australia, and the majority of those are in New South Wales. It makes Australia probably the second-largest nation or location for space start-ups around the world, outside the United States. Australian venture capital is growing and it is starting to invest in space. There are Australian space start-up companies that are actually drawing venture capital from other places: Australian companies have secured money from Boeing Ventures, from Singtel, from the European Space Agency. There's a wide range of them, covering the gamut of new ideas: propulsion, launch vehicles, launch services, ground networks, space situational awareness (SSA), communication systems, the internet of

2 Clark (2018).

things (IoT), robotics, earth observation, small-sat manufacture, and agriculture information from space. The thing about new space is that the lower barriers to entry make a wide range of new businesses possible.

So Australia has world-class space capabilities. We have strong capabilities in world-renowned ground stations[3]. We have strong capabilities in scramjet and hypersonic research. We're among the world leaders in satellite communications, including the NBN satellites, and in particular the way they are integrated into a domestic network. We are world leader in laser-based orbital space debris tracking[4]. And we are one of the world leaders in R and D in position navigation and timing[5].

3 We operate deep-space tracking stations for NASA and ESA, and stations for JAXA (Japan) and China.

4 The Space Environment Research Centre is developing a network of laser ranging orbital debris tracking stations in Australia.

5 Australia is one of few countries with access to all 6 current GNSS systems: 4 global systems (GPS, USA; Glonass, Russia; Galileo, Europe; Beidou, China) and 2 regional systems (QZSS, Japan; IRNSS, India).

We also are seeing an emerging space ecosystem. Many things are happening in low-Earth orbit. The economy is moving there, we are on the cusp of a near-earth space economy and Australian businesses are working into that right now. Finally, the space industry in Australia globally has been growing significantly over 20 years. This growth is attracting private wealth and venture capital. It is one of the hot areas for people to invest in. Australia has leading capabilities in that area and a thriving start-up sector in its own right. And New South Wales is actually leading the nation in a lot of that work. Thank you.

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Space 2.0 — The next world revolution

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Abstract

Will the world make SPACE for Australia, or will Australia make its own SPACE in the world?

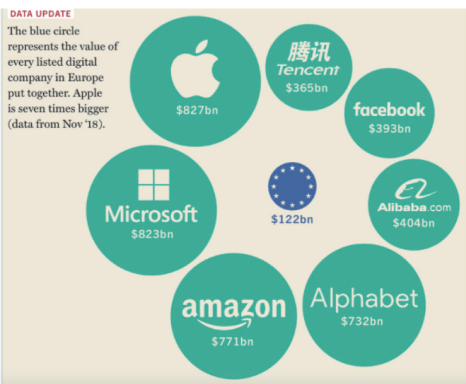
Introduction

We have already embarked on the next world revolution. We are about to witness the biggest technology revolution since electricity was introduced. For Space 1.0 over the past 62 years has all been about "up there," whether that be satellites, humans, or exploration. We have now entered Space 2.0 — Space "down here." It will totally revolutionise the way we live, communicate, and feed ourselves.

The question therefore is will Australia punch above its weight and prosper by this revolution, or will it fall behind and have the new capabilities thrust upon it?

Setting the scene

The world is changing fast. Not only is the world going digital, but just look at which companies are dominating the digital age.



Just ten years ago, only one of these companies, Microsoft, ranked in the top five of the NYSE.

And this total flip is mirrored in the funding for space. For whereas over 80% of funding for space came for governments previously, this has now totally flipped so that over 80% of funding for space now comes from the private sector.

And these changes are related as the biggest companies in the world now realise that they can make billions in "space down here."

Developing the theme

For we are seeing a confluence of new technologies, a time when many new technologies are maturing simultaneously, and it is this conjunction and integration that will change the world.

These technologies are, in no particular order, nanosatellites, very smart and small sensors, remote sensing, artificial intelligence, robotics and drones, IoT, apps, and the Cloud and big data — huge amounts of data!

And around the corner there is the awe-inspiring capability of quantum computing.

The onset of the revolution

Within 5 years there will be 100s of thousands of small satellites in low-Earth orbit all involved with things down here.

If you think that is far fetched, Elon Musk has already got certification to launch over 11,000 satellites in the next year or so.

And he has recently (Oct 2019) submitted application for 30,000 more Starlink satellites.

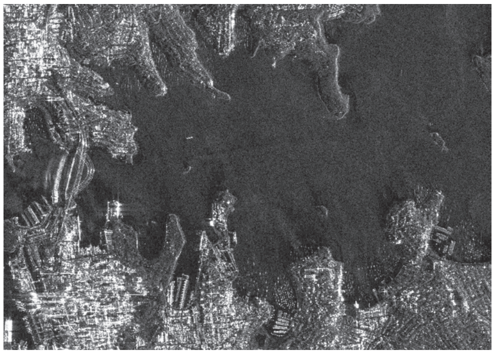
It will change the face of agriculture, mining, and the way we live.

This is indeed a revolution. The United Nations Office for Outer Space Affairs said in 2019 that approximately 8,500 satellites, probes, landers, crewed spacecraft, cargo craft and space station flight elements have been launched into Earth orbit or beyond since 1957, when Sputnik launched. If SpaceX launches 30,000 Starlink satellites in addition to the over 11,000 it already planned, the company will by itself be responsible for about a fivefold increase in the number of spacecraft launched by humanity.

The outcome from the revolution

Think back to the onset of the smartphone revolution and how that changed the world. The first Apple smartphone was introduced on 29th June 2007. And look what's happened since.

So we can look on the onset of 100s of thousands of small satellites as a mesh network of extremely smart smartphones in low-Earth orbit, communicating with each other (probably with laser comms) and equipped with smart sensors that can measure almost anything — day and night.



As an example, here is a SAR image of the Sydney Harbour Bridge, at night, from a single satellite[1].

Just think of the resolution that could be achieved by a phased array of such satellites constituting a huge aperture antenna in space.

General applications

This mesh network of nanosatellites will be the smartphone revolution on steroids — it will be at least 100 times more powerful than the Internet.

Backed by artificial intelligence, deep learning, and data analytics, they will drive the Internet of Things, complete global communications to all corners of the world, and will be the command and control network for robotics down here on Earth: driverless cars will just be a small manifestation of this connectivity.

Specific applications

The Australian farmer of the future will, over breakfast at the kitchen table, download the survey of the farm from space taken the previous day with specific smart sensors, look at the analysis that has been done overnight, check the actions to be taken that day based

1 https://www.sstl.co.uk/media-hub/latest-news/2018/sstl-releases-first-images-from-s-band-synthetic-a

on the analysis, and at a tap of their smart watch, send those instructions to their farm robots, whether they be drones for spraying, tractors for ploughing, or ground robots for picking fruit.

As an example of different farming benefits:

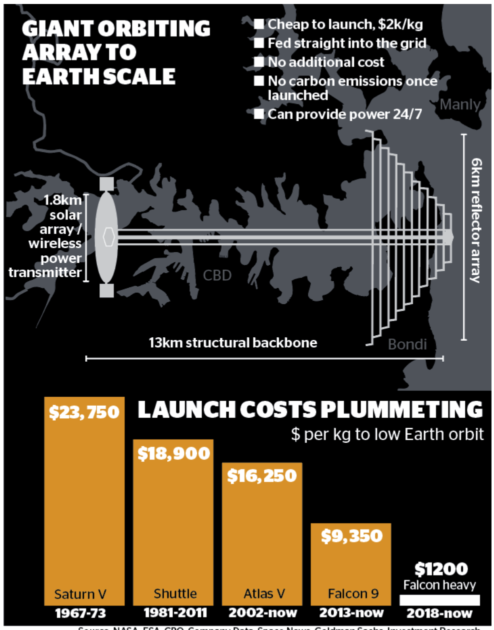
- Broad-acre crops — monitoring plant health & informing precision watering & fertilizers
- Livestock — tracking & monitoring livestock (using sensors on each animal) to locate and also identify indicators of animal stress/pregnancy based on their behaviour
- Water resource monitoring (as outlined by the Farmers Federation)
- Aquaculture — farm site selection, detection of algal blooms, and environmental health

And governments will be able to measure and understand water resources, respond to disasters more quickly, and plan smart infrastructure for the future[2].

This same step-function increase in productivity, efficiency, and environmental protection will be seen across most if not all industries, including mining, transportation, construction, telecommunications, as well as public administration and national security.

Big ideas

What about abundant cheap power? Perhaps a space-based solar power station? This is not as far into the future as one might think. A US-Australia joint venture called Solar Space Technologies (SST) has drawn up an extensive plan to build an orbiting solar-power-generated satellite network that could be operational in eight years[3].



Source: NASA, ESA, CBO, Company Data, Space News, Goldman Sachs, Investment Research

Or even a large solar farm on earth. It does not need to be that big — a solar farm *half* the size of South Australia would provide enough power for *all the world's power needs*.

And with abundant cheap power we could solve our water needs. We have an excess of water — it just falls in the wrong places. With abundant cheap power it can be piped or channelled to wherever you want it, or you can build and operate desal plants and pump water from the coast to wherever it's needed without having to make compromises between environmental, agricultural and town water needs. Indeed energy storage would not even be needed for the pumping, as it would not have to run 24/7.

2 https://www.abc.net.au/news/rural/2019-10-30/farmers-look-to-the-stars-for-crop-monitoring/11648496

3 https://www.theage.com.au/world/north-america/australia-leans-into-space-race-for-solar-power-with-china-20190920-p52ta4.htm

So where stands Australia?

Just about every nation on earth will be launching nanosatellites. Indeed Uber Space is already with us, with an entrepreneur providing a "Trivago-type" web interface where you can shop for a launch.

But the real money will be made with those companies that can invent smart sensors, and more particularly design specific artificial intelligence apps to capitalise on such sensors.

This is the big opportunity for Australia. For we have very smart people and, with the 'tyranny of distance' removed, we can use our smarts to be a big player in this new world.

We have a unique opportunity over the next five years to drag ourselves up from near the bottom of OECD to near the top in terms of commercialisation of these new technologies.

Cyber and resilience

But there is an Achilles heel in all this. By having this uber-connectivity we are building a system that is extremely vulnerable — vulnerable to a cyber attack that will use the connectivity to propagate itself throughout the network.

We need to look at nature and how it is resilient.

The answer is to build diversity into the ecosystem, a diversity that uses natural selection to insulate itself against attack.

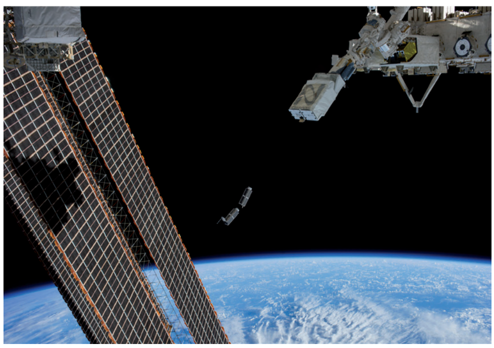
This is possibly the greatest challenge in getting artificial intelligence to work for us positively and to make us resilient against the many manifestations of cyber incursions.

But by having 100s of thousands of nanosatellites in orbit we are in fact building in physical resilience, for they are easily reconstituted and upgraded. And the mesh network of nanosatellites could be reconfigured automatically if it lost a portion of the network.

And using laser comms throughout the mesh network will not only provide much more security, but it will offer some 50 times the bandwidth of modern communications.

Jobs for the future

So the tradies of tomorrow are software developers, coders and app writers, cyber warriors and artificial intelligence gurus. We need to foster these skills in universities and the TAFE so that we can make our own SPACE in the world, and not allow other nations to make SPACE for us. It is simply a matter of economic survival for Australia. Only in this way can we reach the target set for us by the Australian Space Agency of tripling the national GDP space contribution to $12 billion and creating up to 20,000 jobs, all by 2030.



Nanosatellite launch from the International Space Station — it can't get any easier than that. (Credit: NASA)

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Defence space situational awareness: opportunities for Australian industry

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I'm going to talk about the part Defence can play in supporting the Australian space industry.[1] I'll focus on space situational awareness, or, more properly, space domain awareness (SDA). Hopefully, some of the things I will say about things that we're looking to do in Defence, working with our industry, about space domain awareness, might strike a chord, especially given the concern with debris in space.

First, what is SDA and why do we need it? It's understanding the totality of space, the space environment, space weather, what is occurring due to natural phenomena to and human activity. It's understanding that satellites are up there, the debris created by man, the space junk, and the myriad of satellites that are there now and into the future. Understanding objects in space and the environment effects of space allows us to predict what might occur. The worst outcome is a conjunction and a collision between two satellites. These have occurred before and they're probably going to occur again, unfortunately. The most notable example is Iridium 33 and the Cosmos 2251, which, on 10th February in 2009, collided at about 42,000 km/h, creating about 2,000 pieces of debris bigger than 10 cm in diameter. Amazingly, when we're talking about SDA, Iridium was a live satellite and it manoeuvred to miss the other satellite but actually manoeuvred to crash into it.

Why is SDA important? Without a reasonable level of SDA your satellites become more vulnerable. In the military context, that vulnerability moves beyond just space weather and the opportunity for a collision, it extends to an adversary possibly blinding, jamming, spoofing or, in the extreme, destroying one of ours or our allies' satellites We're now pretty well versed in how dependent Australian society is on space for banking, mining, agriculture, entertainment and communications, and Defence has critical dependencies as well for positioning, navigation and timing, timing probably being the most important there, communications as well. If we think that Paul's Space 2.0 has legs — and there's no reason to think that it doesn't — there'll be a dramatic increase in the number of satellites up in orbit very soon. It's becoming more congested, contested and operationally challenging than ever before.

The United States is our great ally, and I'd like to talk about the US Air Force capabilities for a moment, because we are linked very closely. The USAF has many of things that contribute to SDA, including telescopes that look all the way out to geostationary orbits, radars that look at low-Earth orbits, passive radar capabilities, electronic warfare capabilities, satellites in orbit for the express purpose of looking at

1 This is an edited version of the transcript of Dr Lind's talk.

other satellites, and debris, as others have discussed. These all contribute to the space surveillance network that the US runs, and result in the space catalogue, which is positional information and prediction, which the USAF make available for all to see and all to use. Unfortunately it doesn't contain full information. Some of the information is not that accurate and some of it is missing, either by design or by omission.

Satellite constellations are also quite expensive. Even though the costs are coming down, you still really don't want to lose one. The debris could be generated from an avoidable collision and affect many other objects in space. The Kessler effect or syndrome, where we might have a cascading effect of debris, would be something really catastrophic. The movie "Gravity" portrayed the cascading effects that might occur. Indeed, only about 90 of the of the 2,000 pieces of debris from the Iridium/Cosmos collision have decayed out orbit. That's over ten years so it's pretty grim. Once things are up there the debris stays there for a very long time.

Satellite operators, and governments seeking to protect their investments, want assurance and are generally fairly willing to pay for it. Companies have started to seize on these opportunities, such as Exo-Analytic and AGI with networks and space telescopes and radars and complex mission systems that can determine what is occurring and predict conjunctions or collisions and allow us to take evasive action.

Where is Australia in all this, what capabilities does Defence have, and what are the opportunities for Australian industry?

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Where is Australia in all this, what capabilities does Defence have, and what are the opportunities for Australian industry? Whilst our US allies are our great friends and we will share these two sensors, the priorities of the US and Australia don't always align, so there is a need for us to have some sovereign capabilities, so that our sovereign priorities can be serviced as we see fit. As noted above, there are telescopes, radars, lasers, satellites in orbit that can provide us with SDA. Australia probably needs a suite of these types of capabilities because one particular asset can't do it all. For example, telescopes are great to look out into space but they work best at night. Radars are fairly expensive and struggle to look past low-Earth orbit. On-orbit capabilities are coming down in price but they're still expensive and they're very fragile. You certainly can't update them once you put them in orbit.

Defence has been taking the view that Australian industry and Australian innovation is world class in this area and that we should encourage it. So we've been holding a SDA demonstration activity for the last couple of years. Colloquially, it's known as SpaceFest. Companies and universities go there and show their wares. It's in Glendambo in South Australia and what's been coming out of Space Fest has been pretty amazing. The diversity of thinking and the demonstrations of inexpensive and novel solutions for SDA has been pretty impressive. A number of ideas have since been funded by the Defence Innovation Hub and some of them are coming to the end of that funding and are seeking commercialisation for operations. I'd like to describe just a few of these because there are many. This is not an exhaustive list of what our Australian companies have been doing in this sphere.

First, the Western Sydney University neuromorphic sensor. It works a bit like an eye in that it detects changes in movement in a scene and each pixel is independent of each other pixel. It has an extremely fast integration rate, meaning it sees minute changes. And because it just looks at changes, it has a very small bandwidth so it's easy to send that information around — it's easy to pull that information and send it to where it needs to go. It's proving to be fairly revolutionary and it's not just for SDA: there are other applications for it as well.

Second, Silentium Defence have been looking at passive radar, which is a radar that doesn't use a specific source. In this case, they've been using things like FM radio station side lobes and satellite television station transmission signals as well, so they can detect debris in low-Earth orbit. They look at all the sky at once. Whether it's day or night doesn't really matter. It's relatively inexpensive because it doesn't have a transmitter and it's rapidly developing into a really first-class capability.

Third, FireOPAL — Curtin University and Lockheed Martin Australia have developed a system called FireOPAL which is a network of really simple cameras, each with a solar cell. It takes a picture of the sky every ten seconds, and transmits it via the mobile phone network. They plan to roll out hundreds of these cameras across Australia or the world. The cameras just sit there, powered by the solar panel. Someone comes out every year or two to service the camera and it sends that information back to a central processing. It is extremely effective and it really is an innovation because it's taken really simple things inexpensively and provides a really high-quality output.

Fourth, Electro Optic Systems. They've been at this for a while. They've got incredibly accurate laser-ranging systems which can tell you exactly where your particular satellite might be.

All these innovations are sovereign. They offer opportunities not just for Defence but for commercialisation and export, and it's one of the few areas that I deal with where technology is increasing and cost is decreasing. So it's an exciting time for Defence and Australian industry and we just hope to continue our small part in it.

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Making SPACE for Australia: Rapporteur's summary

The Royal Society of New South Wales and Four Academies Forum, Government House 7th November 2019

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Abstract

The Royal Society of New South Wales, with the Four Academies, held a Forum on 7 November 2019 with the title "Making SPACE for Australia". In the course of the day, a series of talks covered a spectrum of topics selected to inform the audience of recent developments, opportunities and challenges that Australia is likely to face as it becomes a more active participant in space activities than has been evident for many years. This paper is a summary of the day's proceedings, that draws on the verbatim record of the Rapporteur's summing-up on the day, modified as appropriate, for inclusion in *The Journal and Proceedings of the Royal Society of New South Wales*.

Introduction

I will begin my review of today's meeting with a few comments about myself, to provide some context for my remarks.

I think it's fair to say that I am somewhat more pragmatic than others when it comes to conversations about Australia's place in space. I tell things as they are, and not as some people would like them to be.

One of my last jobs in Defence, was to work with some senior officers to establish what became the Defence Space Office. Before the office was set up in 2002, we had disorganised groups of men and women in different services and in the Defence central part as well. They were brought together, initially under the ægis of the Royal Australian Air Force (RAAF).

I'm also the person, and Dr Clark has said this in public, who bears some responsibility for the Space Agency. In 2011–12, I was asked by the Space Industry Association of Australia (SIAA) to win the bid and then run the International Astronautical Congress in Adelaide in 2017. The success of that congress was such that Christopher Pyne and others in government at the time: saw an opportunity to gain some political capital and to avert some unwelcome and potentially damaging criticism.

I think that Minister Pyne was terrified that the world's space agency heads were going to turn up in Adelaide and ask the government, "So, what are you lot doing?" and he didn't have an answer. Effectively, the success of IAC2017 created an impetus that government determined it could not afford to ignore.

In the decade before IAC2017, many who advocated for Australia to take a more active role in civil and commercial space activities blamed the government for not being interested and looked to government leadership and investment. However, with respect to the IAC, the industry, such as it was, through the SIAA, took responsibility for our future. We organised the conference, we raised the money and we pulled it off. This brings me back to a comment made to the audience earlier today: it's not about "them", it's about "us." Let's stop talking about "It's their responsibility." Get rid of "their" and insert "I" and "we" and "us," instead. When we make these substitutions, we are defining our role and accepting responsibility.

The Australian Space Agency

Australia absolutely needs a space agency and I say that definitely and unequivocally because there are some bits about the agency that I think are concerning. First, it's tiny. 23 staff, I think, as of today or tomorrow. Second, Dr Clark, who is an inspired choice as the CEO, is part-time. Third, three of the members of the advisory group — it's not even called a board — are either dual nationals or US citizens. Do we not have nine Australians who are competent and capable to advise our own government about space matters? I think this is a dreadful look and if I were the Minister for Finance and the Treasurer, who ultimately fund the Agency, I'd be questioning the seriousness of our commitment on the basis of these three points alone.

Australia's space history. Kerrie Dougherty talked about the technology developments and advancements in Australia's space journey. My PhD focuses on the public policy dimensions of how we got to where we are. Basically, it's by good luck, happenstance and complete serendipity. There is no plan, and never has been. In the 1980s Sir Russell Madigan and his Minister, Barry Jones (Minister for Science). failed to make the case for space so the money asked for was cut away by the Expenditure Review Committee Prime Minister Howard scrapped the Space Office altogether. Today, there is an unholy truce between CSIRO and the Agency. CSIRO, somewhat cheekily, has branded itself as Australia's national space science agency. This is simply confusing and unhelpful. There is one space agency in Australia and it is not CSIRO.

Defence and space

From a government perspective, the money in space in Australia has been and always will be in the Department of Defence. There is a lot of money for space capabilities in the forward investment program of the Department. Some of the money that Dr Clark mentioned today is coming in through the civil sector and can be counted that way. However, these are early investments by companies that are positioning themselves to try to win a forthcoming Defence contract, measured in billions, for remote sensing capability. Their business cases are built around Defence and not the civil sector per se.

My plea is to understand the enduring drivers first America is our strong ally and space activities lie at the heart of the alliance relationship. I make no judgement here about whether this is good or bad, I simply say that, it is. Pine Gap especially has been in the past, is today and will be for a long time to come the long pole in the operational element of the alliance tent. We also host, for civil missions, the Tidbinbilla facility near Canberra.

In hosting these facilities, we take advantage of our geography. We are equidistant between Europe and North America in longitude terms. In terms of latitude, our location in the Southern Hemisphere also bestows great advantage, including for our astronomers. because they can look out from the Southern Hemisphere through the disc of our galaxy, the Milky Way, and see things that are not visible from observatories in the Northern Hemisphere.

In summary, I come at the problem of Australia's place and future in space from a hard-nosed perspective and approach humanity's overall approach to space activities in similar vein.

Ultimately, sovereign states will make the key calls. I think they will be driven to strategies of restraint as they come to understand the damage they may do to themselves as well as their adversaries if denied the benefits of Earth observation, satellite communications and even fundamental research. I think that a variant of the policy of mutually assured destruction (MAD), that characterised the nuclear stand-off in the Cold War between the USSR and the USA will emerge to provide a de facto policy and regulatory environment for space. An urgent question for Australian policy makers is to determine what role Australia seeks to play, as a middle power, in designing the space security architecture of the future. Sovereign states have common cause in creating a regulatory regime, for space that has little to do with peaceful uses in the interests of humanity and much to do with realpolitik.

Summary of the day

The Governor

Governor Beazley gave an inspiring speech which made an excellent introduction to the day. She talked about the conversation being of singular national importance. She mentioned both the military and non-military applications and spoke about Australia's unique location, which is our differentiator.

I was worried when she referred to all of us here as being scientists. So often when space is discussed in public it is linked automatically and uncritically to science: divorced from ordinary people. Common phrases, such as "This is not rocket science" and "she has a head like a planet" reinforce this view. As we heard today, space is also about ethics, law, morality and politics. And we need more broad engagement. The challenge to all of the Learned Academies, not just the science academy, is to take an action to think about each academy's role and contribution with regard to the future of Australia in space, and human activity in space more broadly.

Keynote Address: Professor Kewley

Professor Anne Green introduced Professor Lisa Kewley from the Australian National University.

Professor Kewley gave a wonderful keynote address. She told us how astronomers are pushing the boundaries closer and closer to the Big Bang and the beginning of time and to our universe. And she spoke of the 200-strong team that she leads through the ARC Centre for Excellence in All-Sky Astrophysics in 3D. Astronomy is an Australian research strength and Professor Kewley provided compelling evidence of this fact.

Session 1. Australia in the space age

Professor Jane Hall, the President of the Academy of Social Sciences, Australia (ASSA), moderated the panel with the title Australia in the Space Age. The panel members were: Ms Kerrie Dougherty (Australia's foremost space historian), Dr Megan Clark (Head of the Australian Space Agency), Dr Kimberley Clayfield (CSIRO) and Dr Adam Lewis (Geoscience Australia).

Ms Dougherty noted that Australia really began to cut its teeth on space science in 1957 in the context of the International Geophysical Year (IGY). Our initial focus was on upper atmospheric research which, in those days, was vital because of our concerns about the threat of nuclear war and radioactive fallout.

In the 1950s, Australia's space interests were tightly linked to those of the United Kingdom. Although Prime Minister Menzies, looked more to London than to Washington, the times were changing. Arguably, space activities accelerated the process whereby the USA displaced the UK as the "Great and powerful friend" to which our national security interests were most closely aligned.

I was growing up in the 1950s. I recall conversations between Mum and Dad and my grandparents about Mr Menzies going to London and wondering why he seemed not to be paying similar or even greater attention to the United States. As a six year old, I recall being taken outside on a cold Ballarat night to look up and see Sputnik flash across the sky, not quite understanding what it was that I was seeing. I did understand that I was witnessing a gamechanger in human endeavour. Thanks to Ms Dougherty for grounding us in what Australia has done in space in the past.

Dr Clark provided an update, through a report card, on the Australian Space Agency's progress. She explained a little about the $150 million that is being invested by the Australian Government with NASA in the Artemis Moon/Mars program. In my view, this is an example of policy on the run. The Prime Minister was keen for a good news "announceable" from his visit to Washington. Investing in a space mission with NASA seemed to fill that need supremely well. In fact, there was an immediate and severe backlash in Australia, notably from farming communities that had endured years of crippling drought. On his return to Australia, the Prime Minister immediately flew to Dolby in Queensland to announce additional drought relief funding. This suggests that proper consideration in government about the second- and third-order effects of the investment in Artemis had not occurred. Somewhat cynically, we know that $150 million buys a State Dinner at the Trump White House. This is not to say that there won't be some good from Australia's involvement in Artemis. Mining companies in Western Australia may well be major contributors and beneficiaries because of the knowledge and experience with advanced robotics and automation. Woodside already has a good relationship with NASA in these technology areas.

Dr Clayfield from CSIRO spoke about CSIRO's space significant heritage. I was a little concerned, though, when she said that. "NASA placed its trust in Australia." Why would NASA not place its trust in Australia? It seemed to me there was an element of cultural cringe that simply is not required. Our science and research agencies may be small by global standards but the quality of their work is second to none. We have nothing to apologise about with respect to quality and we have significant expertise in operating ground stations of all types.

Dr Lewis gave an excellent talk about Geoscience Australia (GA), that focussed in particular on remote sensing. He gave us examples of the sorts of things that are being done by GA, in particular with the Data Cube project and how that has application around the world. He is leading an initiative to have the Data Cube put into a number of African nations, initially those in the Sahel.

At the end of this session there was conversation around STEM and STEM education. This is one area where all in present have a role to play. Not enough Australian students are studying STEM subjects in their higher secondary years and at the tertiary level as well. Perhaps space science and engineering can serve as a vector that helps to mitigate this situation. At present we are simply not producing enough men and women in this country who are numerate and who can in fact keep our economy and industry running. This is a challenge to us all.

Session 2. Space law, security and ethics

The second session was moderated by Ms Donna Lawler. Donna runs a space law consultancy in Sydney and previously was legal counsel in the space business of Optus. The members of this panel were Professor Steven Freeland (Western Sydney University), Lieutenant Ben Piggott, RAN (Visiting Research Fellow, UNSW), Dr Nikki Coleman (UNSW Canberra).

Professor Freeland had one key message that space "is not a lawless frontier." He made the point that there is a lot of regulation and a lot of cooperative behaviour between nations in the conduct of space activities. Norms of international behaviour in space are emerging that countries dare not violate. Certainly, nations do breach international law and there is no police force, or night watchman to call them to account.

In 2007, the Chinese did behave badly when they conducted an anti-satellite test that shot down one of their own satellites and created a massive debris field. As a consequence, the Chinese suffered international opprobrium that they still feel. There are lines in the sand, and in space that Steven talked about and that countries dare not cross. I suspect that the Chinese learnt a pretty tough lesson in 2007 and we won't see a repeat test any time soon.

Lieutenant Piggott gave a splendid talk about the military and geopolitical challenges in space in his capacity as a student at UNSW. In real life, Ben is a submariner. He's moved from worrying about the submerged environment to thinking about the heavens. I thought that his last slide was compelling because it broke down the complexity of his topic in a form that was easy to comprehend.

Dr Coleman spoke about space ethics and how there are actually questions beyond the technology that we do need to address in order that we have a space environment going forward from which all of humanity may gain benefit. The enduring question is how to sufficiently synchronise selfish with common interests to ensure that the space environment remain open and accessible to all. As mentioned already, perhaps there is place for some form of mutually assured destruction policy in space — as was in place during the Cold War to prevent nuclear war. Fear of loss is a big motivator.

Session 3. Space and people

The third session was moderated by Ms Annie Handmer, a post graduate student at the University of Sydney. The members of this panel were Dr Jonathan Webb (Science Editor at the ABC), Dr Alice Gorman (a space archæologist from Flinders University) and Ms Ceridwen Dovey (a writer and regular contributor to *The New Yorker*).

Dr Webb affirmed that space and dinosaurs are sure vectors to get children excited about anything. He gave us three wonderful words: mystery, danger and wonder. We need to apply them to our STEM disciplines and to STEM itself. A question might be how to make mathematics mysterious, not necessarily dangerous, but certainly wonderful? If we could figure out some magic around that, we might be in a better place in terms of our future workforce.

Dr Gorman explained briefly the disciplines of archæology and heritage, and how they differ. She then showed how they relate to each other and more broadly to environmental management. She concluded her remarks with an extremely pointed and important comment: that we are some of the few remaining people on Earth who will actually view the heavens, through relatively uncluttered night skies. This is something that our grandchildren and certainly their children will simply not experience. That's profound and might be considered a call to arms.

Ms Dovey provided a challenging critique of the behaviour of some people who have attained cult status in the context of space exploration. She spoke of an alternative, and from her viewpoint, desirable set of behaviours, that she acknowledged some might judge to be naïve, irrational and idealistic. The arrogance, and the ignorance of Elon Musk, in launching a car into space for no purpose beyond advertising, comes to mind in this context. Paul Scully-Power (see below) painted a different picture of developments in space, one that is more likely to eventuate.

The challenge for this audience is to decide whether we want the space environment described by Paul to come about, or has Ms Dovey described an alternative to which we might aspire? If we want change, we are we willing to do to help to bring that change about? This is a conversation that we've got to start and put into our communities. It's a difficult conversation to have because it's not the norm and it challenges the economic basis of our society: sufficiency would be valued more highly than growth.

Session 4. Australia's space economy: prospects for the future

The fourth and final session for the day was moderated by Dr Susan Pond, a senior leader in business and academia, notably in the medical research sector. The members of this panel were Dr Paul Scully-Power, the first native-born Australian to travel to space, Mr Bill Barrett, a Sydney-based space industry consultant, and Group Captain Jason Lind from the RAAF, with responsibilities for space.

Mr Barrett outlined the size of the global space market and of the growth potential of the Australian market. He quoted figures that indicate that investment in space is moving from governments to commercial companies. He also talked about lower barriers to entry to space which helps countries such as Australia to become involved.

In 2002, not long before I retired from the RAAF, I was the security specialist on the Australian team that negotiated Australia's early involvement in the Joint Strike Fighter (JSF) project. At present, through the Centre for Defence Industry Capability (CDIC) in the Department of Industry, Innovation and Science (DIIS), I am helping Australian companies to win some of the work share for the JSF.

This is incredibly difficult to do for two reasons. First, the United States' export control regime, especially the International Traffic in Arms Regulations (ITAR), make it very difficult for technology, even for relatively simple and small components, to be transferred from the United States to Australia or any of the other 13 other nations participating in the JSF project. Second, anything that gets built for aeroplanes must be built to the most exacting standards of quality control and assurance. Few Australian companies are capable of meeting these exacting standards.

Also, our aerospace industry has been used to supporting a fleet of 70-odd jets in the case of the RAAF's fighter force. Suddenly we're now preparing our companies to support 4,000 jets worldwide over a 40-year period. This means that our companies have to think differently, they have to be equipped differently and they have to meet standards that they never, dreamt about.

All of that may be hard enough. NASA, however, as we become involved in the Artemis program, is going to be even more demanding and more exacting. It is possible that for mass-produced satellites, some of these production standards will reduce. However, for missions that involve putting people in space, going to the moon and onto Mars, there will be nothing but the best and the most demanding quality control and assurance processes put in place for every single component in these vehicles.

The extent and importance of Australia's future involvement in space activities is not, in my view, a lay-down misere. There are some enormous challenges. They are good challenges because we have an opportunity to build some Australian companies that can compete globally in the most exacting of technology and manufacturing areas. A lesson from the JSF project that is likely to apply to the Artemis program as well is that financial commitment to the project does not mean that Australian companies will win work. Not only will our companies need to demonstrate capability and quality, they will also need to be competitive on price. This represents an enormous challenge for business owners, process engineers and investors.

Dr Scully-Power, as noted above, provided a counter view to Ms Dovey, saying, "Look, it doesn't really matter what you'd like to be the case, this is what's going to happen." Dr Scully-Power provided a set of numbers, in support of his argument.

Group Captain Lind provided a Defence perspective. He explained that Australia does not have a lot of Defence space capability at present. He emphasised the importance of the US-Australian relationship and gave provided examples of Australian companies and universities that are doing some innovative and substantial work with regard to space situational awareness.

Building on this point, I am a director of the "space junk" CRC, more formally the Space Environment Research Centre, that has its headquarters at Mount Stromlo near Canberra. For those of you who live in Canberra and for those of you who might be visiting, God willing and all being well, some time in February next year there will be a very bright yellow laser that you will be able to see as far away as Goulburn. Our plan is to use this laser to demonstrate that we can move the orientation of a number of small space objects using the pressure of laser light. In the course of SERC's life, it has produced 25 PhDs. And this, of course, is the purpose and the strength of the CRC program. The laser into space is the cream on the cake but it's the increase in knowledge and skill that really matters. SERC is a compelling example of how Australia is building a space workforce that will help the nation to define its place in space in the latter part of the 21st Century.

Summary

Summarising our meeting in a very few words:

1. Our geography is our differentiator. We should think about that in everything that we do with regard to space
2. The environment is rapidly changing, as many of our speakers have pointed out
3. There are capabilities in Australia, developing in the research sector and nascent in industry. Let us understand and play to those strengths
4. There is certainly tension between the civil and the defence realms in space. And perhaps an even bigger tension emerging between public and private investment in space as we've heard as well.

Acknowledgements

Finally, let me add my thanks to the Royal Society of New South Wales for inviting me to be part of this gathering, to the Governor for allowing us to use this wonderful venue and to all of you all for coming.

Thank you very much.

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Obituary

Lord Robert (Bob) May OM, AC, FRS, FAA, FTSE, DistFRSN (Baron May of Oxford)

8 January 1936–28 April 2020

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If I had to choose one word to describe Bob May[1], whom I knew as a scientist, activist and friend from the late 1960s, that word would be "integrity." Bob was a seeker after truth, and his integrity was absolute. He was a lover of games, and saw science as a game of trying to understand the world and how it worked. His success at this game took him to the heights as President of the Royal Society of London and the recipient of many scientific honours. He also had a powerful sense of social responsibility. This was one of the factors in his move from pure physics to study the problems of ecology, and which eventually led to his accepting a position as Chief Scientific Adviser to the U.K. Government and becoming an outspoken spokesman for conservation and the dangers of climate change.

Bob was famous for his directness, which most of us who knew him or worked with him experienced at some stage in our lives. It was coupled with a strong sense of fairness, and a complete disregard for rank or privilege. The privileged members of a certain Sydney club learned this to their cost when the Sydney University chess team, with Bob at the head, turned up for a tournament scheduled to start at 8pm, only to be informed by a waiter that the members were still eating dinner and would be down when they were ready. Bob's very direct response was to break open the cupboards containing the chess sets, set up the boards, and start the chess clocks at 8pm in the opponents' absence.

When he received the Order of Merit in 2002 (a personal gift from the Queen, restricted to 24 members) Bob was thrilled, but not overawed. He reputedly found himself trying to explain Fermat's Last Theorem to her. "Don't worry, ma'am" he said, seeing the expression on her face, "there won't be a quiz."

Bob was an excellent teacher, and would list the points that he intended to make at the beginning of a lecture, and tick them off as the lecture proceeded. He carried this practice through to his many public lectures in later life, which covered topics ranging from chaos theory and the spread of BSE and AIDS to global warming and the wiles of politicians. In his honour I adopt

1 Much of the information in this obituary has come from Bob's colleagues and friends. The quoted passages, where not otherwise acknowledged, come primarily from an ABC Radio National interview with Robyn Williams in 2011 (https://www.abc.net.au/radionational/programs/scienceshow/australian-scientific-superstars-no.1---robert-may/3745700)

the same practice in this obituary, which puts some emphasis on Australian aspects. It will cover:

- Early days as a physicist at Sydney University (to 1972)
- Transition to Professor of Zoology at Princeton (1973–1988)
- Moving to England as Royal Society Professor (joint between Oxford University and Imperial College London) and Fellow of Merton College, Oxford (1988–2020).

Early days at Sydney University (to 1972)

Bob's parents separated when he was seven, and he and his younger brother grew up in the home of their grandparents. He attended Sydney Boys' High School, where his experience of the inspiring chemistry teacher Lenny Basser stimulated him to begin the study of chemical engineering at Sydney University in 1953 (shades of Nobel Laureate Paul Dirac, who began his career in theoretical physics studying electrical engineering at Bristol University). He was also a member of the all-conquering debating team, and later claimed that this gave him a useful training for his dealings with politicians.

All engineering students took the same first-year courses, which involved honours chemistry, honours mathematics, but only pass-level physics. Bob sat in on the honours physics lectures as well, because some of his friends were doing it. When it came to examination time, where he was only obliged to take the pass physics exam, he decided to try the honours exam as "an interesting game," even though he hadn't studied for it. He came top. Eventually he switched to physics and mathematics, gaining his B.Sc. (Hons) and the University medal in 1956 and a PhD in 1959.

I once teased him about his choice of subjects, and suggested tongue-in-cheek that he had switched to physics because it was easier than chemistry. I received the indignant reply that he had come top in chemistry as well, but found physics more rewarding.

After the then-obligatory time "overseas" as a lecturer in applied mathematics at Harvard University (where he met his wife Judith[2], then an undergraduate student at Brandeis), Bob returned to the physics department at Sydney University in 1962. Those were heady days. Professor Harry Messel, brought in to run the School in 1952, had raised it from a state that Bob later described as "rather moribund" to a world-class status in many areas, particularly in astronomy, cosmic ray research and plasma physics, with Bob publishing prolifically in the latter.

Messel also established the International Science School to encourage bright high school students to follow careers in science. Bob was especially pleased when the Federal Government later established (through the School) a prize for Leadership in Science, named at Bob's suggestion after Len Basser. Basser taught eight eventual Fellows of the Royal Society of London in the course of his career, including a President (Bob) and a Nobel Prize winner (John Cornforth). He also taught a number of other future science professors, including the pharmacologist Garry Graham, and Hans Freeman, who did a post-doc with Linus Pauling before returning to set up Australia's first X-ray diffraction laboratory at Sydney University.

Bob summarized the Physics School's activities in an article "Profile of a Physics Department" for *The Australian Physi-*

2 Judith née Feiner.

cist ("single issues fifty cents per copy") in June 1970. By this time he was knocking on the door of a chair, and had in fact been offered one in theoretical physics at the rival University of New South Wales. It was an offer that he probably used as a lever to secure one of Sydney University's first two personal chairs at the age of 34 — an early example of his unobtrusive but very effective political ability, where he characteristically used directness as a cover for subtlety.

The 1970 article was a classically sardonic May production, and hardly calculated to endear him to some of his colleagues. Speaking of the possible (but artefactual) quark tracks observed by the cloud chamber group, he wrote "The group is currently famous (or notorious) for its identification … ". Commenting on the video lectures to large first-year classes, he said "The kindest thing to say about these telly lectures is that they are improving; certainly an inordinate amount of work is being put into them."

But he gave credit where credit was due, pointing out for example that "more than half the 50-odd pulsars so far catalogued have been found by the Mills Cross group." He could also be quite funny about his own theoretical work. "Some of this work makes contact with experiments," he said "and some of it is so abstract as to be quite indefensible." He also liked word play. Speaking of one of his own major theoretical contributions: "Following on from S.T. Butler's seminal work in the field of direct nuclear reactions (or, more colourfully, *stripping reactions* [my emphasis]), the group has developed a new approach … ".

Sometimes the gags went a bit far by today's PC standards. He thought that the activities of the Computer Department, situated within the School of Physics, would be "of lesser interest to the readers of this journal" but added as a footnote "Actually, the procedure by which the computing department selects its pulchritudinous programmers *would* be of fairly wide interest. Unfortunately, the department's published research on this topic is as scant as the mini-skirts themselves."

He could hardly have got away with that these days.

In general, though, the article gave a fair (if colourful) assessment of the environment in which Bob found himself in 1970. His wife Judith and daughter Naomi were very central to that environment, which may have changed drastically when the parents smelled smoke coming from the kitchen early one morning. Bob told me proudly at dinner that night that the smoke had come from four peaches that little Naomi (then 3) had put on the stove top and turned the elements up to various levels to compare the effects. He was convinced that she would become a scientist, but she eventually became a prominent Californian artist.

Bob finished his article by describing "the other minor projects which keep the theoreticians quiet." These included "topics in the behavioural sciences (e.g. The Theory of Voting); and playing bridge at lunch time."

I met Bob through bridge, and we even won the Australian Universities championship together. Bob was very keen on his bridge, although inclined to become rather emotionally involved. Former post-graduate student Robert Hewitt told me of the time when Bob threw his cards at a window in frustration. Unfortunately, the window was open, and the cards had to be retrieved from the car park below.

The two Bobs were also involved in bringing more students to the department. In those days, different departments in the Science faculty could attract PhD students with scholarships by awarding them first class honours as undergraduates. It became clear that physics was losing out since it had stricter standards. The two Bobs set about quantifying the standards depending on a score of credits, distinctions and high distinctions earned over the first three years of undergraduate study. That made it difficult for any department to suddenly promote students to 1st class honours.

Bob's great pride was the time that we beat the U.S. National team; an event that he never failed to remind me of, no matter what the subject of our conversation or email exchange might be.

Non-bridge players can skip the next two paragraphs, although they bear on what follows. Briefly, we were non-vulnerable against vulnerable opponents, and playing a weak no trump system. I had passed, the opponent on Bob's right had passed, and Bob found himself with a hand containing just one jack. He knew that his left-hand opponent must be loaded.

So he opened one no trump! A brilliant psychic gamble, knowing that I wouldn't dump him in the soup because I had already passed, and that he could hardly lose more than the Americans would otherwise gain. The Americans were so flummoxed that they ended up in game when they had a lay-down grand slam, which our partners at the other table duly found, and which turned out to be the difference between the two teams.

Bob was not the only bridge enthusiast in the Department. Professor Stuart Butler was another, and I was rather awestruck to find myself in his and Charles Watson-Munro's company when Stuart was recovering from a heart attack, and Bob had decided that bridge would be an appropriate therapy. I ventured the comment that they must be really pleased to have Bob in the Department, and received the rather grumpy reply from Stuart that it would be OK if he could ever be persuaded to talk about physics.

Because Bob was already starting to think about the problems that would occupy the rest of his life. One of these was game theory — working out the best strategies for interacting with other people on the assumption that they were using *their* best strategies. I occasionally pulled his leg that his outrageous bid against the U.S. team was his first and only experimental investigation of this topic.

In fact he was just about to publish a paper[3] on one aspect of game theory. It was his first outside the realm of pure physics, and concerned with how to get the fairest result possible in an election.

That topic was no accident. Bob was very concerned with fairness, and with applying rigorous mathematical thinking to social questions. Harry Messel had been pushing him to think about even broader issues, and how to apply physics to biology in general. The linking factor was the burgeoning movement for Social Responsibility in Science. It was driven by sociologists like Sol Encel and Stephen Hill FRSN, along with science teacher Telford Conlon and physics professor Peter Mason from Macquarie University. Especially, from the point of view of this obituary, it was driven by Sydney University zoology professor Charles Birch, later to be a founding member of the Club of Rome.

3 "Some mathematical remarks on the paradox of voting." *Behavioral Science* **16**, 143–151 (1971)

Bob was enthusiastically involved, and this was how he found his way almost by accident into the field of ecology. He said, in his interview with Robyn Williams, "In discovering what I was being conscience-stricken and socially responsible about, I had read a book by Ken Watt on ecology and resource management.[4]" It espoused the view, common at the time and supported by observation, that complicated ecosystems would be more stable than simpler ones by virtue of their very complexity.

Bob, being Bob, was sceptical, and decided to check out the question mathematically. He found that the opposite was the case. Large complex systems with random links between their members should, in fact, be *less* stable.

The resultant 1972 *Nature* paper[5], which has had over 2000 citations, took the ecological community by storm, and has provided the foundation for much of its activities ever since. The theorem that Bob proved (which had been proved earlier by Eugene Wigner in a physics context) became known as the May-Wigner theorem, and the disagreement between ecological theory and observation was called the May paradox. Resolving it has been one of the central goals of ecological science. In principle it is easy to resolve since, as Bob once said "Ecosystems are the winnowed products of evolution, they are not random." But "what are the special structures that … reconcile exploiting more niches, having more species and being more complicated with robustness against disturbance?" The question is an important one in our increasingly disturbed world.

4 Kenneth E.F. Watt *Ecology and Resource Management: a Quantitative Approach*. New York: McGraw-Hill (1968).

5 "Will a large complex system be stable?" *Nature* **238**, 413–414 (1972)

Charles Birch, the co-author of the leading textbook on the subject, was fascinated by Bob's discovery, and acted as midwife in what followed. Briefly, Bob was due to take a sabbatical break, working on plasma physics at Culham in the U.K. and astrophysics at the Institute for Advanced Study in Princeton. Birch wrote to his biological friends in both places, urging them to deflect Bob towards more ecological pursuits.

The plan worked a treat, and population biologist Robert MacArthur, then suffering from advanced pancreatic cancer, even urged Bob to take his Princeton chair after he had gone. He was especially impressed when Bob saw immediately the mathematical solution to an important problem in niche overlap with which MacArthur had been struggling for some time.[6]

But Bob was happy in Sydney, and returned to do his thinking there. He did it in some odd places. One of these was the bridge table, where I more than once found myself landed in a surreal contract because Bob had manœuvred the bidding so that he could be dummy and get on with some calculations on a small piece of paper on the corner of the table.

Another favourite thinking place was the tennis court. Bob was an avid player, and with his friend Rod Cross could often be found practising on the university courts on a Wednesday afternoon. Bob was by now doing numerical calculations of population growth and decay, and plotting the resultant graphs using a programmable calculator (he hated programming the university's bigger computers). The calculator was in the Third Year laboratory, and supposedly

6 Robert M. May & Robert H. MacArthur "Niche overlap as a function of environmental variability" *Proceedings of the National Academy of Science of the USA* **69**, 1109–1113 (1972)

for the use of students, but Bob took it over, rather to the dismay of the students and staff member in charge. It was so slow (especially by today's standards) that he had to check it out after every second game to see whether the program had finished. That calculator should really be in a museum, since it played a central role in the development of chaos theory.

The tennis competitions took place on Saturdays in Sydney's Eastern suburbs, where Bob could not access his calculator. He could not bear to be mentally idle, though, so set up a chess board at the side of the tennis court, with the clock to be tapped between games.

The tennis games had an interesting later upshot. Rod became an expert in the physics of tennis racquets, and a frequent consultant to the International Tennis Federation. He attended an ITF meeting in London in 2003, and suggested that Bob be invited to give the after-dinner speech, which was a great success. The following year the ITF gave Bob free tickets for the Wimbledon finals. He and Judith found themselves sitting next to Michael Parkinson, and Judith, who along with Bob seldom if ever watched television, asked him what he did for a living!

Transition to Professor of Zoology at Princeton (1973–1988)

It was Judith who stimulated Bob's move to Princeton. Some Australian ecologists (especially at ANU) had been urging him to join their groups, but Judith argued that Princeton was a chance that might not come again. So, according to Bob "I pick[ed] up the phone, rang the chairman John Bonner, and said 'Have you fixed on Robert [MacArthur]'s successor or are you still looking?'" When told that they were still looking, Bob continued "I've changed my mind. I'd like to do it." Bonner said "Great" and that was that.

The work poured out of him, in what Bob described as the most productive period of his scientific life. He edited the standard textbook *Theoretical Ecology: Principles and Applications*. He expanded greatly on his seminal work on ecological networks and niches. And he laid the foundations for chaos theory.

The latter came about as the result of a puzzle. Bob had been working in Sydney on a key equation, derived by the Belgian mathematician Pierre Verhulst as long ago as 1838, which describes how population growth must slow down as it approaches the limit of the resources available, and even become negative if it overshoots that limit.

The equation is oh so simple, but behaves in an extraordinary way depending on the rate of growth, first breaking into "boom" and "bust" regimes at around a population tripling rate, and eventually breaking into wild (chaotic) oscillations at a critical higher rate (just above 3.596), called the "point of accumulation," with the symbol lambda.

Bob couldn't figure out what was going on. Outside his office in Sydney, he had a notice board. According to James Gleick in his book *Chaos*, there was at one stage a notice that read "What the Christ happens when lambda gets bigger than the point of accumulation?" In fact, as Bob once told me, the language was rather more colourful than that.

Eventually, in Princeton, he figured it out, and produced one of his most famous papers "Simple mathematical models with very complicated dynamics[7]," which has been cited over 7500 times. In that same year

7 *Nature* **261**, 459–467.

he also produced the wonderfully quirky "Ecology of dragons[8]," in which he discussed (among other things) the over-exploitation of dragons for pharmacological purposes, which may have led to their extinction. It was a theme that was to reappear in more serious vein many times in his later career. He later used it cleverly to suggest that climate change may well lead to a resurrection of sleeping dragons from their slumbers[9].

During his time at Princeton, Bob also became the chairman of the university research board. It was a position for which he turned out to be ideally fitted. He also chaired a committee to discuss the safety of the university's recombinant DNA research, and made sure that the local community was included in the discussions.

Bob would also return to Australia frequently during this time, and lectured at the International Science Schools that had been set up by Harry Messel in 1966, 1968, 1972, 1985 and 1987. On these occasions he would always contact Bob Hewitt ahead of time and ask him to round up "the usual suspects" for a game of bridge.

But things were moving. In the U.K. Professor Sir Richard Southwood from Merton College, Oxford, and others were conspiring to bring Bob to the U.K., with the bait of a Royal Society Professorship (joint between Oxford and Imperial College London) and a Fellowship of Merton College, not to mention the croquet lawn and real tennis court.

Move to England (1989–2020)

Bob's career in the U.K., later described by his Merton College sponsors as "stellar," swung wildly between the theoretical, the practical, and the bureaucratic. Much of it is covered in the many obituaries that appeared after his death. Here I can cover only a few highlights.

One undoubted highlight was his work with Roy Anderson at Imperial College. Together, the two built on Bob's earlier work to develop the now-accepted framework for epidemiological modelling[10]. "Mathematical epidemiology" became a field of biology, "central to understanding the dynamics and control of infectious disease."[11] It proved to be of great value in understanding and controlling the AIDS epidemic in Africa, the BSE outbreak in the UK, and the worldwide SARS and COVID-19 epidemics.

During this time Bob moved frequently between Oxford and London, although Oxford was always his first choice. I once asked him where he stayed in London, and he replied that he and Judith had a flat in Chelsea. I must have expressed some envy, because he went on to say laconically "Well, I have won a few prizes."

He certainly had. They included the Balzan Prize for biodiversity, the Copley medal of the Royal Society, the Japanese Blue Planet Prize for "contributing significantly to the improvement of the global environment," and the Crafoord Prize for ecological research. The latter is awarded

8 *Nature* **264**, 16–17.

9 Andrew J. Hamilton, Robert M. May & Edward K. Waters "Here be dragons," *Nature* **520**, 42–422 (2015).

10 R.M. Anderson & R.M. May "The population dynamics of microparasites and their invertebrate hosts," *Philosophical Transactions of the Royal Society of London B* **291**, 451–524 (1981)

11 J.A.P. Heesterbeek & M.G. Roberts "How mathematical epidemiology became a field of biology: a commentary on Anderson and May (1981) 'The population dynamics of microparasites and their invertebrate hosts' *Philosophical Transactions of the Royal Society of London B* **370** 20140307 (2015) http://doi.org/10.1098/rstb.2014.0307

for disciplines that complement those for which the Nobel Prizes are awarded, and is of similar value.

Bob also found his way into the power structures of various organizations where he thought he might be able to promote his social responsibilities, and especially his concern with conservation, and with making science more a central art of public dialogue. He became a trustee of Kew Gardens in 1991, and of the Nuffield Foundation in 1993, driving its student programmes. He was appointed to the Joint Nature Conservancy Council in 1994, and also became Chairman of Trustees of the Natural History Museum in the same year. Later, he would join HSBC's Corporate Sustainability Board, become an adviser to Tesco's Sustainable Consumption Institute, and join the U.K.'s Climate Change Committee.

He also began to give public lectures. Ian Sloane FRSN was present at one of these[12], organized in conjunction with Bob's visit to Australia for a conference "Chaos in Australia." The lecture was at the Powerhouse Museum, which seats around 300. But many more were present, and to accommodate them all Bob suggested that he give the lecture twice. It was a roaring success on both occasions.

The biggest surprise of all, though, was when he became Chief Scientific Adviser to the U.K. Government under John Major, and then Tony Blair.

Chief Scientific Adviser to the U.K. Government (1995–2000)

The tales of Bob's time as a scientific adviser are legion. He was certainly direct in his approach. Bob himself told the story of a meeting in the Cabinet office where he said of one proposal "that's absolute bullshit." As he left, in company with William Waldegrave, the latter said "I suspect that's the first time anyone's ever said 'bullshit' in the Cabinet office. But it shouldn't be the last."

One obituary reported that Bob was reproved by the cabinet secretary for swearing on the grounds that it was the first time that the f-word had been used in the Cabinet room. Sir Nicolas Bevan, former secretary to the Speaker of the House of Commons, wrote a letter pointing out that it was not the first time, and described the time in 1973 when Edward Heath had described a paper under discussion as "f***ing awful."

Bob had a great deal of respect for Tony Blair, whom he described to me several times as being "very bright." It was a compliment that he did not extend to very many other members of the Government, and he generally made a point of avoiding them and only speaking to Blair directly. That was as far as he went in talking with me about his dealings with politicians. He may have been very direct, but he also knew how to keep a confidence.

One of Bob's major goals as Government Chief Scientist was to explain the importance of science to policy makers, and to guide the ways in which it was used. One of his first actions was to produce a report on the efficiency of British science, showing that it was the most efficient in the world when it came to global impact.

It was while he was preparing this report that a British food research group came under press attack for wasting public money, after being awarded a spoof Ig Nobel Prize for studying how breakfast cereals became soggy when milk was added. In fact, the research was entirely funded by industry, but that didn't stop the press. Bob was jus-

12 As was your humble editor — REM.

tifiably annoyed, and wrote a sharp letter to organizer Marc Abrahams demanding that no more of these prizes be awarded to British groups.

Marc showed me the letter once, and it certainly was a beauty. Unfortunately it had the opposite effect, including my own Ig Nobel in 1999 for using physics to work out the best way to dunk a biscuit. This was the consequence of a project that I had used in my efforts to make science more accessible by showing how scientists think about everyday problems. One of my most treasured possessions is the letter that I received out of the blue from Bob, whom I had not seen for some time, congratulating me on the success of my endeavours.

Things took an interesting turn in the next year, when our mutual friend and colleague Sir Michael Berry (like Bob, a Royal Society Research Professor), along with real Nobel laureate André Geim, were offered an Ig Nobel Prize for using a magnet to levitate a frog. This was again work with a substantive purpose (to show that this theoretically possible effect could be realized in practice), and the frog was chosen as a quirky-sounding subject of about the right weight. Michael felt constrained to write to Bob (who, as then President of the Royal Society, Michael liked to refer to as his "boss") about whether he and André should accept the award. Eventually they did, making André the only person in the world to have an Ig Nobel Prize *and* a real Nobel Prize.

Another of Bob's actions was to prepare guidelines for scientific advice to Government, where he advocated "a presumption of openness in explaining the interpretation of scientific advice" — a presumption that was unfortunately diminished, and eventually lost by subsequent governments.

Sadly, he was unsuccessful (as all subsequent holders of the post have been) in persuading the majority of politicians about the importance and significance of science. "It would be quite helpful," he said at the end of his tenure "if some members of government found out who I was."[13]

President of the Royal Society (2000–2005)

Bob was knighted during his tenure as Chief Government Scientist, and it was as Sir Robert May that he was elected as President of the Royal Society of London in 2000, following in the footsteps of such luminaries as Isaac Newton, Joseph Banks, and T.H. Huxley. Bob commented that the majority who supported his candidature were keen that the Society should become more involved in public affairs, but there was a substantial minority who did not approve.

He had had the idea while in his Government role that the best way to hold an enquiry into an issue where science was the focus was "to get some scientific peer who had not been involved to get a group of scientific experts to give an analysis of the lessons to be learned." The lessons in this case concerned mad cow disease (BSE), but Bob's idea was not taken up, and the very expensive Phillips Inquiry took place, which Bob later described as "a legalistic enquiry that would go on for years until everybody was safely retired." The Phillips Inquiry did in fact take three years, cost £60M, and came to at least one wrong conclusion (that the disease was due to a rogue prion as a spontaneous mutation).

13 Sadly, it has taken the COVID-19 pandemic to induce politicians in the U.K. and Australia to act on scientific advice, at least on medical advice. We can still hope for action on climate science advice. [Ed.]

With his new role in the Royal Society, Bob had another chance. The problem this time was foot-and-mouth disease, and the government agreed to ask the Society to hold an independent enquiry along the lines that Bob had suggested earlier. The enquiry cost around 1% of the Phillips enquiry, and produced its report in less than 12 months. The report was also effective, causing the EU to change its rules on vaccination so as to minimize the chances of the problem being repeated.

Bob was not afraid to voice his opinions, and in his role as President of the Royal Society he publicly accused President George W. Bush of "fiddling while the world burns" by ignoring climate change.[14]. He would later point out in a lecture to the Royal Society of Chemistry[15] that the very phrase "climate change" had been invented by a Bush adviser to displace the more specific "global warming."

His scorn for sloppy thinking was not confined to politicians. I was present on one occasion at the Royal Society when Bob was in the chair at a meeting where a prominent biologist attempted to give a physics parallel to a biological effect. "That's wrong," said Bob loudly.

Bob's "in your face" comments about major issues with a scientific component (especially climate change) sometimes caused controversy, and provoked opposition from those with vested interests[16] but set a trend for the Society that continues to this day.

14 https://web.archive.org/web/20050315035945/http://www.commondreams.org/headlines05/0307-03.htm

15 https://www.youtube.com/watch?v=_rFUC_5hBwI

16 https://www.thegwpf.org/images/stories/gwpf-reports/montford-royal_society.pdf

Member of the House of Lords (2001–2017)

In 2000 the Blair Government established a "House of Lords Appointments Commission" whose job was to make recommendations for the appointment of non-partisan life peers. The very last time that we met in 2017, Bob told me gleefully "You just applied for them." And he did, wanting to be known as Lord May of Woollahra. But it seems that the *Australian* protocol people were not happy with this idea, and so he became The Lord May of Oxford.

But why did he want to be a Lord at all? The answer may lie in his suggestion years earlier about the use of scientific peers to lead enquiries. It was a role that he could still usefully serve, especially after his term as President of the Royal Society was over, and he took full advantage. He sat on the Science and Technology Committee, and contributed to 53 debates in his usual incisive style.

He also sat several times on the Economic Affairs Committee, and thereby hangs a tale. In the wake of the 2008 financial crisis Bob teamed up with Andy Haldane, now the chief economist of the Bank of England and regarded by *Time* magazine as one of the 100 most influential people in the world, to examine this crisis between a network of financial institutions. The idea was to examine the network from the perspective of Bob's ecological network theory, and to see whether this offered any ideas for avoiding future crises. It did, and the result was the brilliant "Systemic risk in banking ecosystems"[17].

17 Andrew G. Haldane & Robert M. May "Systemic risk in banking ecosystems," *Nature* **469**, 351–355 (2011).

But there was a snag. Bob told me that they tried all five of the major economics journals, and that it was rejected by all of them. That is why the paper was eventually published in *Nature* — a premier journal for scientists, but not read by economists. Perhaps they should.

Bob certainly enjoyed his time in the House of Lords — including the bridge competition, where I would get regular reports about his success (especially when he won a brilliancy prize). But his success in using it as a lever to advance the cause of science in political decision-making was perhaps more problematic.

He had more success when it came to the many public talks that he was now giving. The Darwin lectures of 2011 were a particular example, where he spoke[18] on the topic "What does the future hold?" and argued that the rise in fundamentalism in both East and West is a reaction to the cooperative change that we need, but which would mean sacrifice of individual liberties (or, worse still, property).

He also gave talks on science advice and policy making, based on his experience as Chief Government Scientist, where he had begun his tenure with the belief that his job was to speak truth to power. As he said in one talk[19], he and other scientists sometimes found this difficult because politics has a different tribal culture. This was especially so when it came to public expressions about risk. With the MMR vaccine, for example, he was rapped over the knuckles for using the scientists' precise expression "There is no evidence that there is anything to worry about," when his political masters wished him to say "There is no risk" or, at worst "There is negligible risk." Nor were they interested in his comparisons with measles, where the risks have been quantified.

Bob was at his best in *explaining* science to non-scientists in an exact but understandable way. His abrupt, incisive style was less suited to getting over the message about what this meant, even though he was well aware of "how inherent uncertainties and imprecisions in the area of human social behaviour can affect our ability to gather and interpret statistical information about ourselves."

But no other style, whether that of Attenborough, Sagan, Asimov or others, has been notably more successful in making science more a part of our culture. Bob was a living example of how this could be achieved, and perhaps that is his greatest legacy — that, and the stimulus that he gave to so many of us.

Bob's portrait in Australia's National Portrait Gallery shows him with a taxidermy specimen of an extinct thylacine on his lap. To him, science was a game, but the conservation of our planet and its inhabitants certainly was not. His induction as a Distinguished Fellow of the RSNSW at Government House was presided over by Marie Bashir, whom his wife Judith remembers as "saying such nice things." We could do with more like him, even though in many respects he was totally one of a kind.

— Len Fisher

18 https://www.youtube.com/watch?v=PRato4F6ZyM

19 https://www.youtube.com/watch?v=_rFUC_5hBwI

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Royal Society of NSW Awards 2020

James Cook Medal

The James Cook Medal is awarded from time to time for outstanding contributions to both science and human welfare in and for the Southern Hemisphere. Nominations for the 2020 award will close on 30 September 2020. A letter of nomination and the nominee's full curriculum vitæ should be sent to the Awards Committee at awards-nominations@royalsoc.org.au. The medal will be presented at the Society's Annual Dinner.

The Clarke Medal and Lecture

The Clarke Medal is awarded each year for distinguished research in the natural sciences conducted in Australia and its territories. The fields of botany, geology, and zoology are considered in rotation. For 2020, the medal will be awarded in **Botany**. The recipient may be resident in Australia or elsewhere. Nominations for the 2020 award will close on 30 September 2020. A letter of nomination and the nominee's full curriculum vitæ should be sent to the Awards Committee at awards-nominations@royalsoc.org.au. The medal will be presented at the Society's Annual Dinner. The date and location of the Clarke Memorial Lectureship will be arranged as mutually convenient with the medal's recipient, usually at the recipient's institution.

Edgeworth David Medal

The Edgeworth David Medal is awarded each year for distinguished research by a young scientist under the age of thirty-five (35) years on 1 January 2020 for work done mainly in Australia or its territories, or contributing to the advancement of Australian science. A letter of nomination and the nominee's full curriculum vitæ should be sent to the Awards Committee at awards-nominations@royalsoc.org.au by 30 September 2020. The medal will be presented at the Society's Annual Dinner.

History and Philosophy of Science Medal

The Society's History and Philosophy of Science Medal is awarded each year to recognise outstanding achievement in the History and Philosophy of Science. A letter of nomination, the nominee's full curriculum vitæ, and a letter from the nominee agreeing to the nomination should be sent to the Awards Committee at awards-nominations@royalsoc.org.au by 30 September 2020. The conditions of this award allow for self-nomination. The medal will be presented at the Society's Annual Dinner.

The winner will be asked to submit an unpublished article, drawing on recent work, which will be considered for publication in the *Journal & Proceedings of the Royal Society of New South Wales*. Manuscripts will be peer reviewed.

Warren Prize (Lecture & Medal)

The Warren Prize, which includes $500, is awarded from time to time to an early- or mid-career researcher in engineering or technology whose work has achieved national or international significance. The research must have originated or been conducted principally in New South Wales. Entries may be submitted by researchers from any public or private organisation. Application must include submission of an original paper to the *Journal & Proceedings of the Royal Society of New South Wales* by 30 September 2020. The paper should review the body of research conducted by the applicant and demonstrate its relevance across the spectrum of knowledge — science, art, literature, and philosophy — that the Society promotes. A judging panel appointed by the Royal Society of NSW will determine the winner. The Medal will be presented at the Society's Annual Dinner. The time and location of the lecture will be arranged as mutually convenient with the award's recipient.

Archibald Ollé Prize

The Archibald Ollé Prize of $500 is given from time to time to the member of the Society who has submitted the best paper to the *Journal & Proceedings of the Royal Society of New South Wales* in any year.

Liversidge Lecture

The Liversidge lectureship is awarded biennially for research in chemistry. The lecture is presented in conjunction with the Royal Australian Chemical Institute. The lecture will be published in the *Journal & Proceedings of the Royal Society of New South Wales*.

The Jak Kelly Award

The Jak Kelly Award was created in honour of Professor Jak Kelly (1928–2012), who was Head of Physics at University of NSW from 1985 to 1989, was made an Honorary Professor of University of Sydney in 2004, and was President of the Royal Society of NSW in 2005 and 2006. Its purpose is to encourage excellence in postgraduate research in physics. It is supported by the Royal Society of NSW and the Australian Institute of Physics, NSW branch. The winner is selected from a short list of candidates who made presentations at the most recent Australian Institute of Physics, NSW branch, postgraduate awards.

Royal Society of New South Wales Scholarships

Three scholarships of $500 plus and a complimentary year of membership of the Society are awarded each year in order to acknowledge outstanding achievements by young researchers in any field of science. Applicants must be enrolled as research students in a university in either NSW or the ACT, and must be Australian citizens or Permanent Residents. The winners will be expected submit a paper to the *Journal & Proceedings of the Royal Society of New South Wales* (which will be peer reviewed) and to deliver a short presentation of their work at the general meeting of the Society in February 2021 (following their nomination).

Nominations for the 2020 awards will close on 30 September 2020. Self-nominations are allowed for this award. The following documents should be sent as a single package to the Awards Committee at awards-nominations@royalsoc.org.au:

- The letter of nomination should clearly state the significance of the student's project
- The student's curriculum vitæ, containing a list of publications, details of the student's undergraduate study, and any professional experience
- An abstract of 500 words describing the project
- A statement of support from the student's supervisor, confirming details of the student's candidature.

The applications will be considered by a selection committee appointed by the Council of the Society and the decision will be made before the end of November. The scholarships will be awarded on merit.

The Poggendorff Lectureship

The Poggendorff Lectureship is awarded periodically for research in plant biology and more broadly agriculture.

Nominations are sought every year, but the lectureship may not be awarded in any particular year. Nominations for 2020 will close on 30 September 2020. A letter of nomination and the nominee's full curriculum vitæ should be sent to the Awards Committee at awards-nominations@royalsoc.org.au. The medal will be presented at the Society's Annual Dinner. The time and location of the lecture will be arranged as mutually convenient with the award's recipient.

The Royal Society of New South Wales Medal

The Society's Medal is awarded from time to time to a member of the Society who has made meritorious contributions to the Society's administration, organisation, and endeavours. Nominations for the award close on 30 September 2020. A letter of nomination and the nominee's full curriculum vitæ should be sent to awards-nominations@royalsoc.org.au. The medal will be presented at the Society's Annual Dinner.

The Royal Society of New South Wales Citation

The Royal Society of New South Wales Citation was introduced in 2019. It is awarded to a Member or Fellow of the Society who has made significant contributions to the Society, but who has not been recognised in any other way. The Awards Committee considers nominations made by a Member or Fellow. A maximum of three Citations in any one year may be awarded. Nominations for the award close on 30 September 2020. A letter of nomination, outlining the significant contribution that the nominee has made to the Society, should be sent to awards-nominations@royalsoc.org.au.

Archibald Liversidge:
Imperial Science under the Southern Cross

Roy MacLeod
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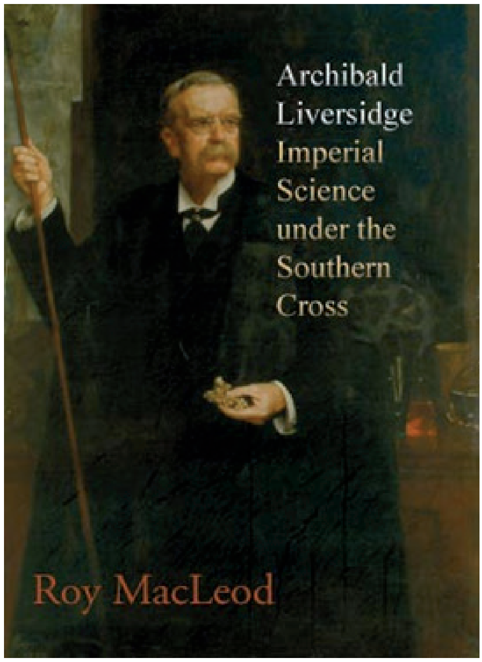

When Archibald Liversidge first arrived at the University of Sydney in 1872 as Reader in Geology and Assistant in the Laboratory, he had about ten students and two rooms in the main building. In 1874, he became Professor of Geology and Mineralogy and by 1879 he had persuaded the University Senate to 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.

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