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AUSTRALIA'S CHIEF SCIENTIST

Growing Australia's STEM industries: Lessons from quantum

Key points

- The rapidly developing field of Quantum Information Science and Technology (QIST) is used as a case study for science, technology, engineering and mathematics (STEM) skills workforce requirements in emerging industries.

- Australia's universities have a strong international reputation in QIST research. Since the mid-1990s, focused government investment including several Australian Research Council Centres of Excellence has greatly increased the scale of QIST research and development, training over 2500 domestic and overseas early career QIST researchers, enhancing career opportunities and generating several spin-off companies. Australian-trained researchers are renowned internationally in QIST and other STEM sectors.

- Australia must significantly grow the number of workers with STEM skills to capitalise on the rapidly developing QIST field, and deliver a projected 16,000 QIST jobs by 2040. A "science first" approach, covering a broad range of promising technologies, is currently being adopted by most countries during the early stages of development of the quantum industry. This new industry requires highly skilled specialists in a wide range of areas including quantum physics, computer science, software, electronic and electrical engineering, overwhelmingly at PhD and Masters levels. Australia needs to compete internationally to attract and retain such talent.

- As a number of other fields mature, technical skills including data science, mathematics, precision manufacturing and nanofabrication, and broader skills including systems analysis, technology commercialisation and business expertise will be required. These will require Bachelor, Diploma and Vocational Education and Training (VET) level qualifications, and need to be predominantly supplied by the domestic workforce. On-the-job training, industry placements and micro-credentials are all likely to play a role in training this workforce.

- The current supply of domestic graduates with STEM skills is not keeping up with the rapidly rising demand in emerging technology industries, many of which require similar skills. Large underrepresented cohorts, including women, low socioeconomic status, First Nation and regional, rural and remote Australians need to be better supported into, and then during, their STEM careers, including better opportunities for non-linear career paths.

- While Australia does not have the scale of private and public funding of some competitor economies, advantages include a strong university sector known for high-quality research, training and connectivity between institutions, and long-term investment. Patient investment in long-term collaboration initiatives between universities, the broader research sector, governments and industry, would be an attractor for leading STEM specialists and students considering STEM as a career.

This short discussion paper has been prepared by the Office of the Chief Scientist to examine the policy settings that led to Australia's world-renowned quantum workforce. Quantum is considered a useful case study for other growth technical industries with similar skills needs.

AUSTRALIA'S QIST WORKFORCE

Development and commercialisation have not traditionally been a strength of Australia's innovation system. From the mid-1990s onwards, a succession of Australian governments undertook a series of reviews and developed research and development (R&D) and innovation policies to respond to the changing economic conditions and increased exposure to the effects of globalisation.

Despite these policy interventions, business R&D expenditure in Australia has continued to be relatively low, falling from 1.2 per cent of GDP in 2011-12 to 0.9 per cent in 2019-20 [1].

Notwithstanding global changes and domestic challenges, Australia's exceptional QIST system was born. Today, Australian-trained QIST researchers are internationally renowned and in global demand [2]. A specific series of investments and policy decisions led to the development of this workforce.

The following sections examine:

- The settings that led to the development of Australia's strong QIST workforce.
- How the policy settings that led to Australia's successful QIST workforce could be applied to other growth industries in Australia.
- How the anticipated demand for workers with skills in QIST and other growth industries will increase over the coming years and what must be addressed to meet this demand.

University research established Australia as an international leader in QIST

Foundations for Australia's success in QIST were built by university-based basic science research teams, which focused on fundamental quantum physics problems. Australia has 22 quantum-related research institutions [3], including 8 universities performing quantum physics research that ranks well above world standard [4].

A critical policy development was the introduction of the Australian Research Council Centres of Excellence (CoE) scheme in the early 2000s. The aim of the CoE scheme was to facilitate transformational research and capacity building in any area of basic or applied research by investing on a larger scale and over a longer time period than existing grant schemes. Strong international collaborations and high-quality training for junior researchers were explicit goals of the scheme [5].

Since 2003, 7 CoEs in QIST areas have attracted $188 million of federal funding (Table 1) and another 5 CoEs have attracted a further $145 million for work which includes aspects of QIST research – a total of $333 million. Significant cash [6] and in-kind [7] contributions from collaborating and partner organisations, typically at 1.5-2 times the ARC funding, brought the total investment in QIST research close to $1 billion. Each CoE has trained around 200 research students (a total of about 2500) and 50 early and mid-career researchers (EMCRs) [5]; many of these students and EMCRs were attracted from overseas, enabling Australia's QIST workforce to grow its capacity [3]. Per capita, this represents a higher training rate of PhD students than the US [8].

Two features of the CoE scheme important to its success were that it:

- Explicitly funded basic science research without commercialisation requirements (although end-user engagement was a key performance indicator).
- Did not prioritise specific research areas. The growth in Australia's QIST capacity therefore happened as a natural consequence of research freedom and excellence in relevant areas.

ARC Centres of Excellence - QIST

Year	Centre	Funding*
2003 - 2011	Centre for Quantum Computer Technology	$24,100,000
2003 - 2011	Australian Centre for Quantum-Atom Optics	$16,950,000
2011 - 2017	ARC Centre of Excellence for Quantum Computation and Communication Technology	$24,500,000
2011 - 2017	ARC Centre of Excellence for Engineered Quantum Systems	$24,500,000
2017 - 2024	ARC Centre of Excellence for Engineered Quantum Systems	$31,900,00
2017 - 2024	ARC Centre of Excellence in Future Low Energy Electronics Technologies	$33,400,000
2017 - 2025	ARC Centre of Excellence for Quantum Computation and Communication Technology	$33,700,000

ARC Centres of Excellence - Related to QIST

Year	Centre	Funding*
2011 - 2018	ARC Centre of Excellence for Ultrahigh Bandwidth Devices for Optical Systems	$23,800,000
2014 - 2020	ARC Centre of Excellence for Nanoscale BioPhotonics	$23,000,000
2017 - 2024	ARC Centre of Excellence for Gravitational Wave Discovery	$31,300,000
2017 - 2024	ARC Centre of Excellence in Exciton Science	$31,850,000
2020 - 2027	ARC Centre of Excellence for Dark Matter Particle Physics	$35,000,000

*at announcement

Table 1: ARC Centres of Excellence in QIST and QIST-related disciplines. Data from [9].

Critical mass and collaboration drive excellence

The success of Australia's Centres of Excellence in building QIST capacity offers insights into attracting, developing and retaining talent in other emerging areas reliant on similar technical skills, including space, clean energy and semiconductors. The number and size of the QIST CoEs facilitated a qualitatively different kind of research and research training to what was previously possible: the number of QIST researchers was large enough for Australia to be an international leader, yet moderate enough for meaningful cross-institutional collaboration with a coherent approach. Instead of quantum teams in cognate areas competing for funding, effort was invested in collaboration. The large size and long timescale (approximately twice as long as typical research grants) of CoEs also made it possible to balance the research risk profile across the centres. Researchers were supported in pursuing promising high-risk, high-gain projects; breakthroughs from some of these have led directly to huge (in excess of $100 million) offshore investment in Australia [10].

International connectivity was an important feature in CoE success: while early CoEs had fewer than 5 formal international partner institutions [11], this number grew to over 15 for later CoEs [12]. Rigorous technical training and mentoring of early career researchers, combined with explicit international collaborative opportunities, made Australian QIST specialists internationally sought-after: in recent years, several alumni from Australia's research community have taken up leadership roles in quantum research divisions overseas [3]. These same settings also facilitated a virtuous brain-gain cycle by making Australia a desirable destination for international PhD students and postdoctoral researchers. A larger domestic QIST ecosystem also meant an increase in secure, desirable long-term job opportunities within Australia, and hence retention of domestic and international talent. The $1 billion investment for expanding Australia's critical technology capability, including funding for 20 QIST PhD students [13], and dedicated industry PhD studentships and fellowships [14], are the most recent initiatives in this area, aimed at leveraging Australia's international reputation to maintain competitive advantage.

The rapidly changing quantum industry brings opportunities

QIST activities have changed fundamentally in the past 5 years, evolving from predominantly academic research and development towards translation. Conservative estimates suggest that commercialisation of quantum technologies could be worth at least $86 billion globally by 2040 [3]. In Australia, this would correspond to $4 billion in revenue, comparable to Australia's present-day wool [15] and wheat [16] industries; and create 16,000 new jobs [3]. These figures do not include further benefits through gains in productivity resulting from using quantum capabilities across a wide range of industries, as well as benefits leading to improved national security.

Reflecting this potential, more than 100 US-based start-ups have attracted more than USD$2.5 billion in venture capital alone over the past decade [8]. In Australia, 17 quantum-related companies have attracted more than $400 million in funding in recent years [17]. Market leaders in information technology (IBM, Google, Microsoft, Amazon, Hewlett Packard and Alibaba [8, 18]) and other areas such as investment banking (Goldman Sachs, Wells Fargo, JP Morgan Chase [19]) have invested in their own in-house quantum research teams. Some large international companies have recently established quantum teams in Australia or partnered with local universities [3].

QIST workforce requirements are broad and change as the industry evolves

Access to a quantum-capable workforce is a major challenge for Australia's rapidly growing QIST industry, as it is for other QIST leaders globally [20, 21, 22, 23, 24, 25, 26, 27]. QIST research, translation and commercialisation require a wide range of STEM skills. These include technical skills in quantum physics, science, software, electrical and electronic engineering, data science, mathematics, precision manufacturing and nanofabrication; and broader skills such as systems analysis, technology commercialisation and business expertise [3, 8, 19]. Specific skill requirements depend strongly on quantum methodology, field of application (quantum sensing, computing or communication) and technology readiness level [28]. Quantum sensors are likely to be deployed in areas such as health and remote sensing within 5 years; quantum-secured financial transactions and moderate size quantum computers within 10 years; and wide-ranging quantum communication and large-scale quantum computers within 15 years [29].

Technologies with longer time horizons, such as for quantum computers, are not yet sufficiently developed to make informed judgements on which technical approaches are likely to succeed, hence a science-first approach must be adopted [25]. Workforce requirements will also change substantially over the next 5-15 years, as different QIST technologies mature, requiring a broad STEM skills base at any given time, including the transition to more VET trained workers.

GROWING AUSTRALIA'S TECHNICAL INDUSTRIES

Short term:
Attract world-leading experts underpinned by domestic research excellence

A broad-based approach to growing new technical industries requires access to STEM talent with postgraduate qualifications [18]. In Australia, approximately half of PhD and the majority of Masters researchers in science, engineering and information technology fields are international students [30]; the situation is similar overseas [8]. In the US, more than half of their international workforce still contributes to the domestic economy 10 years after graduation [8], slightly higher than the rate of retention of international graduates in Australia across all fields of study [31]. This workforce is complementary to training at lower (e.g. Bachelor and VET) levels, which is predominantly domestic [30]. Experience from the quantum industry suggests that a larger fraction of STEM jobs that support development of innovations at higher Technology Readiness Levels [28] will be filled by these domestic graduates [8, 18] as industries evolve.

Other countries are competing for the same international talent, however Australia has several advantages. English-speaking countries attract 70 percent of highly qualified migrants [32]. Australia has a culture that supports ambition and academic freedom and provides the possibility of building varied career pathways. The moderate size of Australia's STEM sector allows connectivity between different institutions and experts. Australia's location, infrastructure and excellence in research and higher education also makes it an attractive proposition for prospective international talent. In general, the vibrant, cohesive and collaborative Australian system can attract overseas researchers and Australian researchers who may have gone overseas to undertake PhDs or post docs.

Australia has fewer opportunities in industry than competitor countries with greater numbers of start-ups and larger industry sectors. In addition to a healthy research sector, attracting international STEM talent at PhD and early/mid-career researcher levels to Australia will require appropriate policy settings in many areas. This is already being deployed by other nations. These requirements include liberal immigration and tax settings, funding for start-ups and mechanisms for technology transfer [33, 26, 34] and government engagement as a technology procurer of choice [35].

Medium term:
Transition STEM graduates to QIST jobs and grow support industries

Approximately one in 5 Australian undergraduate degrees are in Natural and Physical Sciences, Information Technology or Engineering [36]. This skills pool will be essential for the development of many critical industries, including QIST, space, cyber, biotechnology, clean energy and semiconductors [8, 37]. Graduates will need to be upskilled for each of these industries from cognate areas as they enter the workforce.

Workforce training will be most effective if developed collaboratively by education providers and employers. Drawing on a quantum industry example, the Sydney Quantum Academy is a $35 million collaboration between 4 Sydney universities with active quantum research programs, government and industry partners, to train PhD students in QIST-relevant skills, and facilitate entrepreneurship and outreach programs [38]. It is underpinned by a $15.4 million investment from the New South Wales government, and has supported more than 100 QIST PhD students in its first 2 years [39]. Another program, APR.Intern, which has connected approximately 400 PhD students from more than half of Australia's universities with 100 industry partners [40], is a potential national blueprint for providing pathways for graduate students into a wide range of STEM industries. International best practice also includes development and application of micro-credentials [41] and online courses [18].

Long term:
Adapt the STEM pipeline and enable latent workforce participation

University undergraduate participation in STEM disciplines has been growing slowly (Table 2), while PhD student numbers have more than doubled in the past 20 years [42]. However, this increase in STEM student numbers is slower than the projected growth in jobs which require STEM skills, three quarters of which will require at least a Bachelor's degree [43].

Domestic student cohort needs to grow to address the STEM skills shortage

There are further structural challenges. The recent growth in student numbers in STEM fields has been driven almost entirely by international students (Table 2). By contrast, domestic student numbers have either stagnated (Natural Sciences), or fallen (Engineering) since 2017; only Information Technology has seen an increase in domestic student completions, but at lower levels than the increase in international student numbers. Between one half and two thirds of international graduates do not remain in Australia in the long term [31], so the lack of growth in domestic student completions is likely to exacerbate future skills shortages in STEM and related areas.

Domestic and international STEM graduates

	Natural and Physical Sciences*		Information Technology		Engineering		TOTAL
	Domestic	International	Domestic	International	Domestic	International	
PhD	1,101 (-5.1%)	963 (-1.4%)	178 (+28%)	220 (+5.8%)	628 (-1.3%)	928 (+19%)	**4,018 (+3.0%)**
Master	1,168 (+7.3%)	1,698 (+53%)	1,062 (+29%)	14,875 (+193%)	1,488 (-12%)	7,249 (+49%	**27,540 (+88%)**
Bachelor	16,589 (-0.1%)	4,076 (+37%)	4,770 (+24%)	5,875 (+99%)	7,428 (-4.1%)	5,030 (+17%)	**43,868 (+14%)**
TOTAL	**18,958 (0.0%)**	**6,737 (+33%)**	**6,010 (+25%)**	**20,970 (+154%)**	**9,544 (-5.2%)**	**13,207 (+33%)**	**75,426 (+32%)**

Table 2: 2020 completions across broad fields of education, and degree levels. Numbers in brackets are percentage change since 2017. Data from Department of Education, Skills and Employment [30]. *Natural and Physical Sciences includes Physics and Astronomy (8.6% of total Natural Sciences graduates in the workforce in 2020), Chemical Sciences (15.3%), Earth Sciences (13.6%), Biological Sciences (34.5%), and Medical Science, Forensic Science, Food Science and Biotechnology, Pharmacology and Laboratory Technology (28.0%) [60].

School student participation in STEM is declining

At secondary school, the proportion of students taking STEM subjects, including intermediate or advanced mathematics, has decreased by approximately 10% in recent years [44]. There is also a significant shortage of specialist STEM teachers at this level [45]. Those students who do choose to study STEM subjects at university are therefore increasingly underprepared, and this is reflected in their university performance both in Australia [45] and overseas [46].

These issues need to be addressed to provide Australia with a STEM-capable workforce. Initiatives aimed at encouraging STEM graduates into teaching [47, 48], student outreach programs [29], and research projects in collaboration with universities and industry [38] may provide solutions.

The education system is inequitable

There is significant inequity in STEM training and career progression. School academic achievement is a strong predictor of future success in study and post-schooling work [49]. Students with outcomes in the bottom quintile on NAPLAN Year 3 tests (i.e. when they are only 9 years old) are much more likely to choose less academically challenging subjects in the final years of schooling, which limits their future career options [50]. Students from low socioeconomic backgrounds are at risk of poor educational outcomes from their first year of school, with the risk increasing with age [51]. Students from regional, rural and remote areas, and First Nations students, are similarly disadvantaged, with an education attainment gap of up to 3 years compared with their more advantaged peers.

There are also substantial differences in education outcomes between different states and territories [52]. These early disadvantages have been shown to map directly to university performance [46]. Supporting the prospective workforce from these disadvantaged cohorts at early stages of education is likely to yield substantial long-term benefits.

Approximately one third of Australia's population lives in regional or remote areas, and the Australian workforce is less mobile than culturally similar countries such as the US and the UK [53, 54, 55]. Large technology clusters are unlikely to be established outside large metropolitan areas. A combination of industry placements and more accessible remote learning and working [56] may provide an opportunity to engage this latent regional workforce, provided the inequity in school STEM outcomes is addressed.

Gender inequity is persistent

Gender inequity is persistent across STEM fields. Although boys and girls perform similarly well in final-year school physics subjects, more boys than girls study physics at university [57]. Encouragement by mentors, including school and university teachers, and clear articulation of career pathways and the breadth of available STEM roles, will be important for bridging this gap [58, 59]. At present, only one in 5 professionals in physics and astronomy, engineering and information technology is female; this drops to one in ten or lower at senior leadership levels [60].

Having a child imposes a significant barrier on females even having a STEM career: only one in 3 women with university STEM qualifications and in full-time employment in 2011 were still working full-time in 2016 after having a child during this period, compared with more than two-thirds of women who did not have a child. Moreover, almost one in 5 women who had a child left the workforce altogether. The proportion of women leaving STEM careers after having children is even higher in the VET sector [60]. In the research sector, women without children appear to have similar career trajectories to men at early career stages [61], but gender disparity emerges at more senior levels [62].

Lack of job security in academia and lack of clear career pathways outside academia contribute to this bottleneck [42], as does the trailing spouse penalty [63] – the recognition that there are significant career advantages in academia and other professions from mobility [64]. Women are more likely to have partners in full-time employment, and hence more likely to have to navigate the challenges of accommodating 2 careers [65, 62]. STEM-trained women represent a large, highly skilled prospective workforce which is currently underused.

A broad range of career pathways is needed

None of these problems are unique to Australia [66, 67], and many are also evident in non-STEM fields [63], however women in STEM are more likely to leave their field than non-STEM professional women, especially early in their career [68].

Initiatives such as longer-term fellowship appointments and explicit recognition of parental and other carer responsibilities [69, 70] can contribute to tackling this issue. More broadly, there is significant work to do in changing the culture and policies in STEM workplaces to adequately support women and other minority groups in STEM. Strategies for improving retention, not just recruitment, of skilled STEM workers across demographic groups will be a key component of this work. As STEM skills become increasingly essential to a broad suite of professions, career pathways must cover a similarly wide range of possibilities.

CONCLUSION

The strength of Australia's existing QIST workforce, and the policy settings and investment decisions that helped build it, offer lessons that can be applied to a number of Australia's rapidly growing technical industries.

- As skill shortages and the global competition for talent increase, Australia must press its systemic, cultural and institutional advantages to attract technical experts, while continuing to develop and support a diverse domestic STEM workforce.
- Coordinated long-term investment by government and the higher education sector created a critical mass of world-class QIST specialists, and put Australia at the forefront of this emerging industry.
- Further virtuous cycles in other STEM industries can be created through the combination of patient investment in foundational research, coordinated efforts across institutions, world-class STEM education, and support for attraction, retention and development of a diverse STEM-skilled workforce at all career stages.

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