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Working paper

Partners in knowledge creation: trends in Australia-China research collaboration and future challenges

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Abstract

Australia does not have the scale of physical capital, human capital and/or domestic market needed to operate at the international technology frontier under its own steam. This reality means Australia's high-income status depends on being open to cross-border flows of new technologies and creating new knowledge through research collaboration with international partners. Historically, such collaboration has been oriented towards countries such as the United States and the United Kingdom. However, China's emergence as a major source of knowledge creation has disrupted the traditional order. This paper draws on bibliometric data to conduct a preliminary analysis of the extent to which China has emerged as a collaboration partner for Australia. The findings point to China's rise being both rapid and dramatic, irrespective of whether metrics related to the quantity or quality of knowledge created are used. Further, the data point to collaboration with China largely being complementary to that undertaken with more traditional partners in terms of research subject areas. Despite these findings, the future trajectory of Australia-China knowledge creation is uncertain owing to concerns around national security and ethics, deteriorating conditions for academic inquiry in China due to an increasingly repressive political regime and a worsening funding environment for universities in Australia.

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The Australia-China Relations Institute (ACRI) is an independent, non-partisan research institute based at the University of Technology Sydney (UTS). UTS:ACRI's mission is to inform Australia's engagement with China through substantive dialogue, and research and analysis grounded in scholarly rigour.

Key findings

- Australia does not have the scale of physical capital, human capital and/or domestic market needed to operate at the international technology frontier under its own steam. For example, in purchasing power parity terms Australia spends $20-25 billion on research and development (R&D) each year. In comparison, the United States and China both spend in the order of $500 billion. This reality means that Australia's high-income status depends on being open to cross-border flows of new technologies and creating new knowledge through research collaboration with international partners.

- Businesses account for around 54 percent of R&D spending in Australia, compared with 35 percent for universities and 11 percent from government and private non-profit organisations. However, two-thirds of R&D spending by businesses involves 'experimental development', that is, applying existing knowledge to develop new processes, systems, good and services, rather than creating new knowledge.

- Universities are the main institutions in Australia responsible for creating new knowledge in the form of 'pure basic research', 'strategic basic research' and 'applied research'. These classifications account for 90 percent of universities' total investment in R&D. The Australian government has long recognised the benefits from universities collaborating with international partners – subject to regulations such as Defence Trade Controls – and has sought to encourage such interactions.

- In 1998, only one percent of Australian peer-reviewed journal articles – a proxy for the quantity of knowledge created – included a co-author affiliated with a Chinese institution. This made China Australia's ninth largest international collaborator. By 2018, the Chinese share had risen to 15 percent. If 2018 growth rates remain constant, this year China will overtake the US to become Australia's leading international collaborator by this metric.

- In 1998, only four Australia-China articles were in the top one percent of most-cited articles – a proxy for the quality of knowledge created – aggregated across all subject areas. In 2017, there were 389. This means that China is now on the cusp of being Australia's third most important international collaborator by this metric.

- Australia's research collaboration with China and the US is highly complementary. Collaboration with China is oriented towards the physical sciences: in 2018, 29.4 percent of Australia-China articles were in engineering. In contrast, collaboration with the United States is oriented towards the life sciences with 35.3 percent of Australia-US articles in medicine.

- In certain subject areas, Australia's collaboration with China has become vital to knowledge creation. In Materials Science, Energy, Chemical Engineering, Engineering (which includes all other engineering sub-disciplines excluding chemical engineering) and Computer Science, Australia-China articles account for more than 30 percent of total Australian articles. In Computer Science, Engineering, Mathematics, Materials Science and Physics, Australia-China articles account for more than half of Australia's highly-cited papers in these areas.

- Despite the data pointing to the rapid and dramatic rise of China as a partner for Australia in knowledge creation, the future trajectory is uncertain owing to concerns around national security and ethics, deteriorating conditions for academic inquiry in China due to an increasingly repressive political regime and a worsening funding environment for universities in Australia.

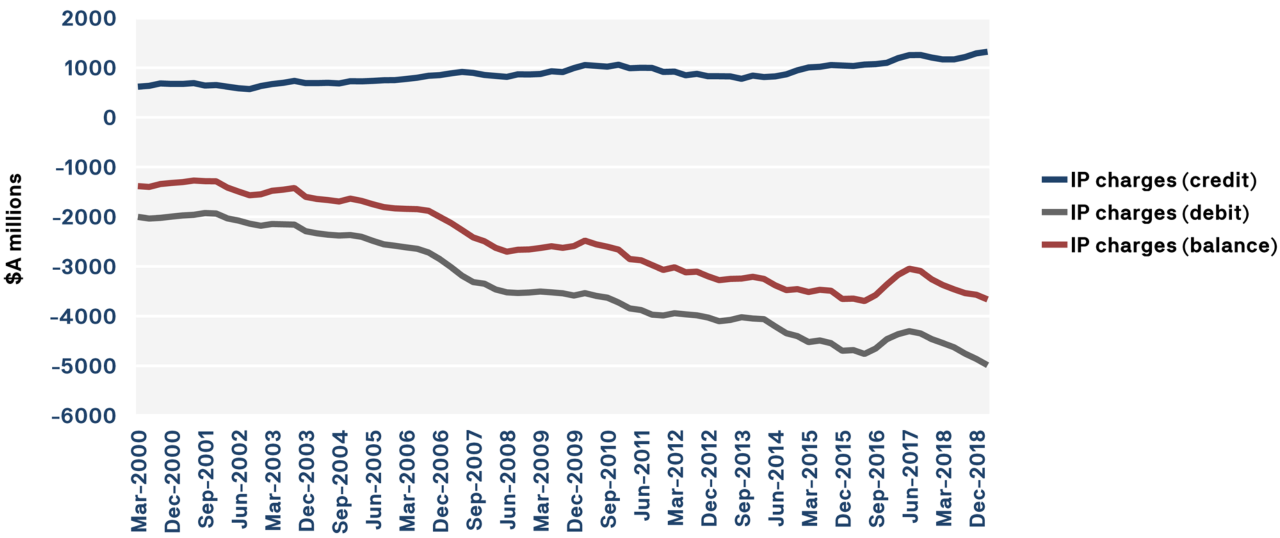
1. Introduction

Australia does not have the scale of physical capital, human capital and/or domestic market needed to operate at the international technology frontier under its own steam. When measured in purchasing power parity terms, the latest data from the Organisation for Economic Cooperation and Development (OECD) show that Australia spends between $20-25 billion dollars on research and development (R&D) each year. In comparison, the United States and China both spend in the order of $500 billion (OECD, 2019). This reality means that Australia's high-income status depends on being open to cross-border flows of new technologies and creating new knowledge through research collaboration with international partners. One outcome of this openness is that Australia has long been a large net importer of intellectual property (IP) (Australian Bureau of Statistics (ABS), 2019) (Figure 1).

Australia's R&D activities are performed by a variety of actors. There is a strong international element in each case. In 2015-16 businesses in Australia spent A$16.7 billion on R&D, accounting for around 54 percent of total R&D spending (ABS, 2017) (Table 1). A proportion of this comes from businesses in Australia that are foreign-owned. For example, the US Bureau of Economic Analysis (BEA) reports that in 2016, majority US-owned business affiliates spent US$852 million on R&D in their Australia-based operations (BEA, 2018). A distinguishing feature of the R&D undertaken by businesses is that it is weighted – around two-thirds of the total – towards 'experimental development'. According to the Australian and New Zealand Standard Research Classification (ANZSRC) 2008, 'experimental development' involves 'using existing knowledge gained from research or practical experience' to produce new processes, systems, goods and services.

Another important set of actors, and the focus of this paper, are Australian universities. Universities are the dominant non-industry investors in R&D in Australia, having spent A$10.9 billion in 2016 (ABS, 2018) (Table 1). While this is A$5.8 billion less than the total spent by businesses in 2015-16, the R&D conducted by universities is weighted towards the creation of new knowledge rather than the novel application of existing knowledge. This includes the ANZSRC classifications of 'pure basic research', 'strategic basic research' or 'applied research'. In 2016, these classifications accounted for 90 percent of the total R&D spend by universities. Collaboration with overseas partners has proven to be crucial for Australian universities. In a 2017 assessment of Australia's innovation system, the Australian government's Department of Industry, Innovation and Science (DIIS) reported that nearly half of the publication output from Australia's top 10 universities featured an international co-author (DIIS, 2017). The

Figure 1. Australia's intellectual property charges trade



Source: ABS (2019)

Table 1. R&D spending in Australia, by sector (A$ millions)

	Businesses	Higher education (2016)	Government and private non-profit organisations (2016-17)
1. Pure basic research	125	2478	122
2. Strategic basic research	883	2019	866
3. Applied research	4796	5280	1831
New knowledge (1-3)	*5804*	*9777*	*2819*
4. Experimental development	10855	1101	460
5. Total expenditure on R&D (1-4)	**16659**	**10878**	**3279**

Source: ABS (2017; 2018a; 2018b)

Australian government has long recognised the benefits from universities collaborating with international partners – subject to regulations such as Defence Trade Controls - and has sought to encourage such interactions (Standing Committee on Industry, Science and Innovation, 2010).

While this accounting at the aggregate level is useful, by only considering all international research collaborations what could be missed are important changes in the pattern of collaboration. Historically, the major creators of knowledge have been researchers at institutions based in countries such as the US and the UK, as seen by their domination of international university rankings. However, the rise of mainland Chinese institutions in particular has disrupted the traditional order. According to the Academic Ranking of World Universities (ARWU) – which ranks universities based on the quantity and quality of their research output – China now hosts 12 universities in the world's top 200, up from two in 2010 (Table 2). Chinese universities are particularly strongly represented in certain research fields. For example, in the field of

Table 2. Number of Chinese and US universities in ARWU top 200

	2010	2018
China	2	12
US	89	69

Source: ARWU (2010; 2018)

Table 3. Number of Chinese and US universities in ARWU engineering/technology and computer sciences top 100

	2010	2016
China	5	19
US	47	29

Source: ARWU (2010; 2016)

engineering/technology and computer science, in 2016, 18 of the world's top 100 universities were in China, up from five in 2010 (Table 3).

The above stylised facts motivate a hypothesis statement that in performing their key role of knowledge creation, over time the reliance of Australian universities on traditional partner countries for collaboration has shifted in favour of China. This paper undertakes a preliminary analysis based on bibliometric data to examine the extent to which China has emerged as a collaboration partner for Australia. Section 2 looks at changes in the overall scale and pattern of collaboration undertaken by Australian universities. This is followed in section 3 by an analysis that is more focused on quality: are changes in the scale and pattern of collaboration in quantity terms also seen with respect to the production of those outputs that have the most impact? Section 4 examines whether there is evidence of Australian researchers collaborating more or less with those in China in particular research subject fields. Are there fields of research where the ability to collaborate with China is now critical to Australia's ability to create knowledge? Alternatively, are there fields where such a situation has not materialised? Section 5 discusses some of the challenges that make the future trajectory of Australia-China collaboration uncertain. Section 6 concludes.

2. The quantity pattern of Australia's international research collaboration

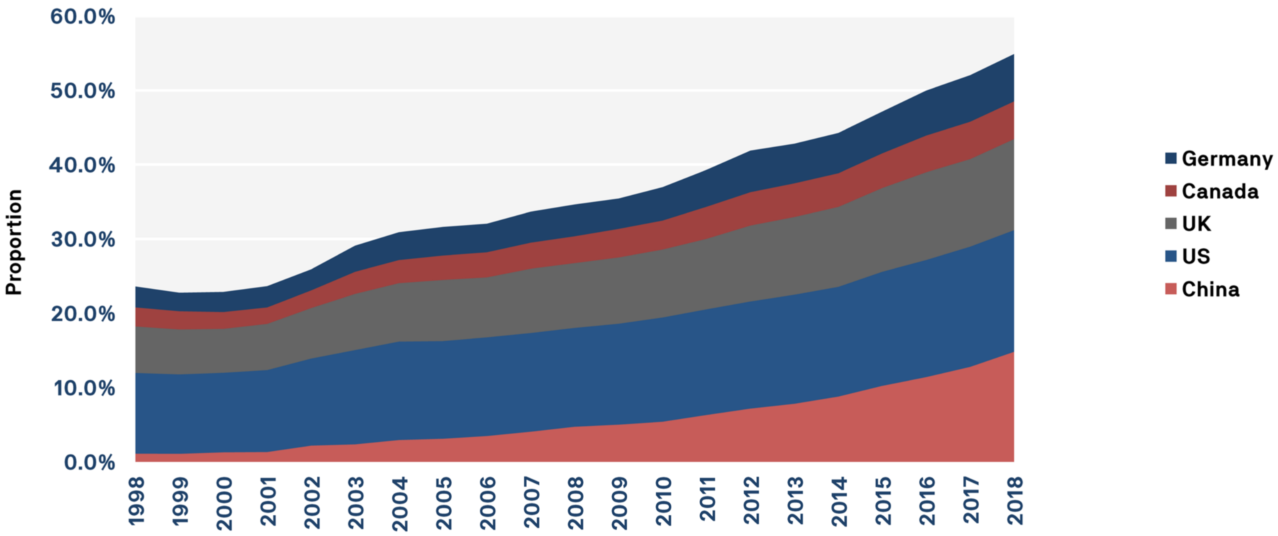
To examine the scale and pattern of the quantity of research collaboration undertaken by Australian universities, this paper uses bibliometric data from Scopus, the world's largest database of peer-reviewed literature. The search was restricted to articles consisting of 'original research or opinion' published in peer-reviewed journals (Elsevier, 2017). Other types of publications, such as conference papers and reviews, were excluded. The scale and pattern of Australia's international collaboration is then inferred by considering the country affiliation of article authors. A single article can have multiple authors affiliated with different countries and an individual author can have more than one affiliation, including one in Australia and another overseas.

To be clear, the country affiliation of article authors is only one possible metric of international research collaboration and for that reason the findings in this paper should be considered preliminary, inviting further research. For example, the Australian Academy of Humanities (2015) argue that simply considering co-authorship across countries fails to capture different modes of collaboration or output across the research spectrum, particularly in humanities disciplines.

That caveat acknowledged, in 2018 Australian researchers produced a total of 72,392 articles – a proxy for the aggregate quantity of knowledge created. This includes all articles in which at least one author was affiliated with an Australian research institution. The total of 72,392 in 2018 was a significant jump from the 22,293 articles recorded in 1998, a 225 percent increase. While this is a notable change in and of itself, even more dramatic developments are seen in the pattern of international collaboration that sits beneath these headline figures.

Figure 2 shows that in 1998, 11 percent of Australian articles, or 2,422 in absolute terms, included an author affiliated with a US institution. This made the US Australia's leading international collaborator. The US share

Figure 2. Number of articles with collaborating country (proportion of Australian total per year)



Source: Scopus (2019)

has grown even further over time. By 2018, the proportion of Australian articles with a US author had grown to 16 percent, or 11,840 in total. Turning to China, in 1998 only one percent of Australian articles, or 248 in absolute terms, included an author affiliated with a Chinese institution. This put China behind the US, the UK, Germany, Canada and four other countries in terms of its collaboration importance. In a bibliometric analysis of Australia's international collaboration in science and technology in 2009, China still did not rate a mention relative to other international partners (Matthews et al., 2009). However, Figure 2 shows that by 2018 the proportion of articles with a Chinese co-author had grown to 15 percent, or 10,732 in absolute terms. In 2017 China surpassed the UK to become Australia's second most important international collaborator by this metric. Just one year later the Chinese share exceeded the UK share by 2.5 percentage points. If 2018 growth rates for collaboration with individual countries remain constant in 2019, then by the end of this year China will have surpassed the US to assume the leading position.

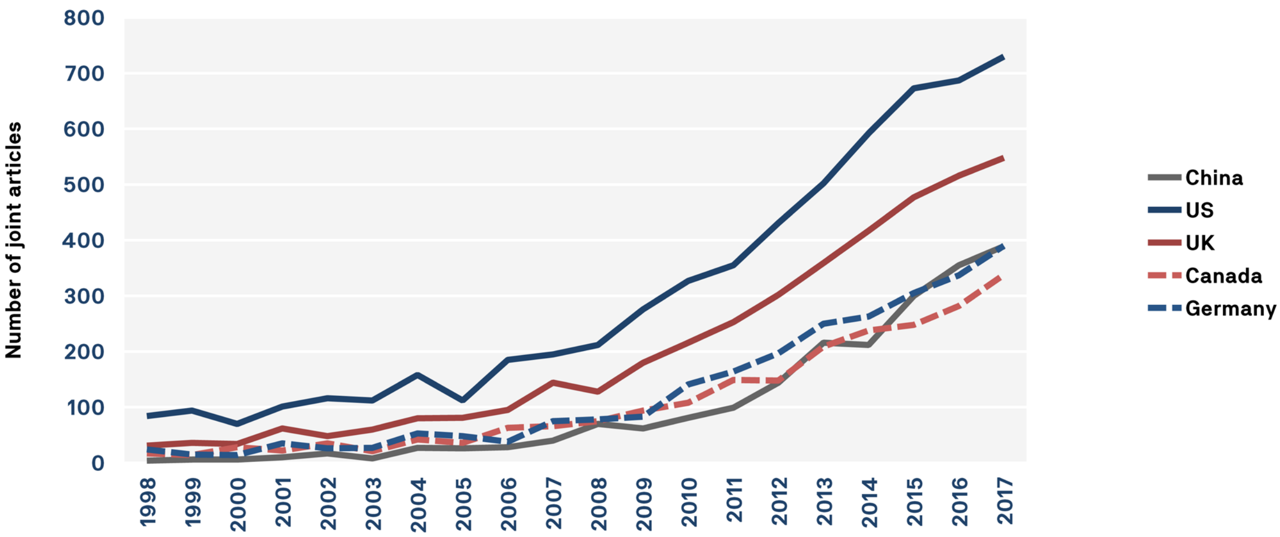
While China's rise as a research partner for Australia has been rapid and dramatic, a similar pattern is seen in other countries. For example, according to the latest data from the US National Science Foundation, China is by far the most important international collaborator for US researchers in science and engineering (NSF, 2018). As a proportion of total US articles in science and engineering that include an international collaborator, 23 percent are from China. This is up from five percent in 2002. Those from the UK are in second place, with only a 13 percent share.

3. The quality pattern of Australia's international research collaboration

A distinction might be made between the importance of international collaboration in terms of the quantity of output on the one hand, and the output of the highest quality or impact on the other. A standard bibliometric measure of the quality/impact of peer-reviewed original research publications is their citation performance. To investigate the quality pattern of international collaboration by Australian universities, this paper draws on citation performance data from the InCites database. The search is again restricted to articles (excluding conference papers, reviews, etc.) published in peer-reviewed journals. The specific metric is the top one percent of most-cited articles in a given year and subject area. These data are available from 1998 to 2018. Under this metric, articles can belong to multiple subject areas and are sorted using the Web of Science subject area schema, which is comprised of 252 subject areas (InCites, 2019).

In 2017 there were a total of 1,550 Australian articles in the top one percent of most-cited articles, aggregated across all subject areas. This represented a 357 percent increase from 1998, in which Australian top one percent articles numbered just 297. When considering the data by country of collaboration, Figure 3 shows that in 1998 there were 84 articles in the top one percent that featured an Australian-affiliated and US-affiliated author. By 2017, this had risen to 730, making the US the most important collaborator for producing top one percent articles with Australian researchers. In comparison, in 1998 there were a total of just four Australia-China articles in the top one percent. This made China the 19th ranked collaboration partner for Australia. However, by 2017 the number of Australia-China articles in the top one percent had grown to 389, putting China in fourth place, only just behind Germany.

Figure 3. Number of joint articles in the top one percent of most-cited articles, by country per year



Source: InCites, author calculations (2019)

4. The research subject area pattern of international collaboration

Data from Scopus (quantity) and InCites (quality) by research subject area provide an even more granular view of Australia's international collaboration. Filters limiting data to peer-reviewed journal articles are retained. It should be noted that because of differences in subject area categorisation between the Scopus and InCites databases, data on the quantity and quality of Australia's international research collaboration by subject are not strictly comparable.

Table 4 uses the Scopus database to show the top 10 subject areas in terms of the number of articles published in collaboration with China and the US in 2018. For example, of the total number of articles featuring an Australian and Chinese affiliation, 29.4 percent were in the field of engineering. Meanwhile, medicine accounted for 35.3 percent of total Australia-US articles. There appears to also be a skew towards natural sciences in Australia's international collaboration, with social sciences comprising a significantly smaller share of the top 10 subject areas in the case of Australia-US collaboration, and not appearing at all in the top 10 with China. However, this could to some extent reflect the nature of the databases used. As Mongeon and Paul-Hus (2016) conclude, these are skewed towards tracking journal articles, an output format favoured by researchers in the natural sciences. Within the natural sciences, Australia's collaboration with China and the US exhibit clear differentiation in the foci of subject areas. While the top three subjects for Australia-China articles are comprised primarily of physical sciences,

Table 4. Top 10 subject areas of Australia's joint research with China and the US in 2018 (by proportion of total joint articles)

Australia-China		Australia-US	
Subject area	**Percent of Australia-China journal articles**	**Subject area**	**Percent of Australia-US journal articles**
Engineering	29.4	Medicine	35.3
Materials Science	20.6	Biochemistry, Genetics and Molecular Biology	17.6
Physics and Astronomy	15.2	Agricultural and Biological Sciences	13.6
Chemistry	14.2	Physics and Astronomy	13.0
Computer Science	13.0	Earth and Planetary Sciences	12.0
Environmental Science	12.1	Environmental Science	9.4
Medicine	10.8	Social Sciences	7.3
Earth and Planetary Sciences	10.7	Engineering	6.9
Biochemistry, Genetics and Molecular Biology	10.5	Chemistry	5.3
Chemical Engineering	9.6	Neuroscience	5.2

Source: Scopus (2019)

Table 5. Top 10 subject areas of Australia's joint research with China and the US in 2018 (by proportion of total Australian articles per subject area)

Australia-China		Australia-US	
Subject area	**Percent of Australian journal articles**	**Subject area**	**Percent of Australian journal articles**
Materials Science	39.4	Multidisciplinary	29.2
Energy	36.5	Physics and Astronomy	26.7
Chemical Engineering	35.1	Earth and Planetary Sciences	26.1
Engineering	34.9	Immunology and Microbiology	24.6
Computer Science	32.9	Biochemistry, Genetics and Molecular Biology	23.7
Chemistry	29.9	Neuroscience	22.4
Physics and Astronomy	28.2	Medicine	19.8
Mathematics	25.6	Pharmacology, Toxicology and Pharmaceutics	18.8
Earth and Planetary Sciences	21.0	Agricultural and Biological Sciences	18.3
Environmental Science	18.3	Psychology	15.9

Source: Scopus (2019)

those for Australia-US articles are comprised primarily of life or health sciences.

Table 5 presents the top 10 subject areas in 2018 for which collaboration with China and the US is most critical for Australia's output. For example, Australia-China articles accounted for 39.4 percent of Australia's total articles in Materials Science. Meanwhile, Australia-US articles in Physics and Astronomy accounted for 26.7 percent of Australia's total articles in this area. Table 5 illustrates that in five subjects Australia-China articles account for greater than 30 percent of total Australian output in these areas. This is a greater exposure in individual subject areas than seen with respect to Australia-US articles, where the proportion is always less than 30 percent. The data in Table 5 again highlights the subject area complementarity between Australia's research collaboration with China and the US, which are skewed towards the physical and life sciences, respectively.

A similar pattern can be identified when examining subject area collaboration with a focus on quality. Data in Table 6 are again drawn from the InCites database. However, rather than the most-cited metric used in Figure 3, a related but distinct measure is presented: highly-cited articles. This metric is defined as the top one percent of cited articles in a given year and subject area, but where subject areas are assigned using the Essential Science Indicators (ESI) subject area schema. The advantage of this schema over the Web of Science subject area schema used for the most-cited metric is that articles are assigned to only one subject area and is comprised of 22 subject areas in total. This assists in the presentation of subject area country comparisons. The main limitation of the highly-

Table 6. Top 10 subject areas of Australia's joint research with China and the US in 2017 (by proportion of total highly-cited Australian articles per subject area)

Australia-China		Australia-US	
Subject area	**Percent of Australian highly-cited journal articles**	**Subject area**	**Percent of Australian highly-cited journal articles**
Computer Science	71.2	Space Science	85.3
Engineering	61.3	Molecular Biology & Genetics	82.9
Mathematics	60.7	Neuroscience & Behavior	80.0
Materials Science	60.4	Clinical Medicine	75.9
Physics	56.9	Physics	64.7
Microbiology	50.0	Geosciences	60.3
Chemistry	46.0	Microbiology	60.0
Geosciences	34.5	Plant & Animal Science	58.7
Agricultural Sciences	27.3	Biology & Biochemistry	58.3
Space Science	26.5	Immunology	55.0

Source: InCites (2019)

cited article metric is that it is only available since 2009, although this does not detract from Table 6 where the focus is only on the most recent year.

Table 6 shows the top 10 subjects where Australia-China articles are most critical to Australia's output of highly-cited papers in these areas. For example, in 2017 Australia-China articles account for 71.2 percent of all highly-cited Australian articles in Computer Science. In the top five subject areas, Australia-China articles account for more than half of Australia's most highly-cited articles in these subject areas. Meanwhile, Australia-US articles in Space Science comprise 85.3 percent of Australia's highly-cited papers in that area. And as with quantity data around subject collaboration, a high degree of complementarity is evident between Australia's collaboration with China for creating quality output in the physical sciences on the one hand, and with the US in the life sciences on the other. Only physics, microbiology, geosciences and space science are common to the top 10 subject areas for both.

This complementarity additionally suggests that the rise in quality Australia-China research collaboration in subject areas like engineering is likely to be mostly independent of the US. Similarly, collaboration with the US in molecular biology and genetics is, in general, not reliant on Chinese partners.

5. Potential challenges

The preceding sections point to two key findings. First, according to bibliometric data, China's rise as a collaboration partner for Australia has been both rapid and dramatic. This assessment is applicable whether metrics relating to quantity or quality are used. Second, China's rise has not been to the exclusion of traditional partners. In fact, it appears largely complementary. The value of collaborating with China is seen most prominently in enhancing the quantity and quality of Australia's knowledge creation related to the physical sciences. Meanwhile, the US not only remains important overall, but especially so in the life and health sciences.

Nonetheless, the future trajectory of Australia-China collaboration in knowledge creation is not certain. One challenge is external pressure being applied to universities to curtail collaboration with China owing to concerns around national security. An allegation is that Australian universities are facilitating an unintentional transfer of sensitive technology with civilian and military applications (dual-use technology) by working with Chinese researchers and postgraduate students connected to the People's Liberation Army (Joske, 2018). In turn this could potentially erode the technological superiority of Australia's security ally, the US.

The nature of this concern is not new to the discourse and policy framework around research and national security. In 2012 the Defence Trade Control Act 2012 (DTCA) was introduced to 'control the transfer of defence and strategic goods technologies and bringing Australia in to line with international best practice'. Just three years later, ongoing concern prompted further reform of the DTCA, with the Defence Trade Controls Amendment Bill 2015 introducing a requirement for researchers to seek permits before undertaking activities that would otherwise contravene the DTCA. In 2017 and 2018, the issue again earned renewed impetus following media reporting on particular university collaborations with Chinese partners (Callick, 2017). In response, then-Minister for Defence Marise Payne appointed Dr Vivienne Thom, former Inspector-General of Intelligence and Security, to conduct an independent review of the DTCA in April 2018 to assess whether it remained fit for purpose (Payne, 2018).

At a Senate Estimates hearing in October 2018, Defence Secretary Greg Moriarty confirmed that there had been no incidents of non-compliance with the Act by universities. Similarly, an audit by the Australian government's Australian Research Council (ARC) of specific projects that critics had argued were problematic revealed no breaches (McGowan, 2018). Nonetheless, those advocating greater restrictions on universities responded that this reflected shortcomings of the DTCA itself. The Department of Defence's own submission to the Thom review argued that the DTCA needed to adapt to 'changes in the security environment' and called for amendments that would grant Defence with greater power to scrutinise Australian universities' research activities (Riordan, 2019). One claimed flaw in DTCA was that it effectively permitted the transfer of sensitive technologies by allowing overseas researchers to be trained in such technologies within Australia. On the other hand, universities and companies – including those from the US such as Northrop Grumman – cautioned against regulatory overreach, arguing that it would stifle the open environment needed for knowledge creation to flourish.

In February 2019 the Thom review concluded that gaps existed in the DTCA – including, for example, a lack of controls for emerging technologies such as hypersonics – and agreed with the Defence submission that these required rectification. It did not, however, find that these gaps justified the 'broad approach implied by the recommendations in the Defence submission' (Thom, 2019). The review instead recommended that, '...Defence should work with stakeholders to develop a practical legislative proposal...' and:

> To ensure that any amendment does not unnecessarily restrict trade, research and international collaboration, the legislative proposal should... ensure all decisions are targeted and based on risk-related consideration of the technology being supplied, the end user and the end use.

There have also been calls from the US for Australian universities to curtail their collaboration with China. In May 2019, US Congressional Republicans introduced a bill to ban student and visiting scholar visas to researchers ‘affiliated’ with the Chinese military. The bill ‘expressly calls on Australia… to enact similar rules to preserve the security of the ‘Five Eyes’ partners’ (Greber, 2019). In July 2019, US Ambassador to Australia Arthur Culvahouse Jr said, ‘[I]t is just impermissible that someone, through a so-called academic exchange, or doing a doctorate or dissertation, can pilfer that [dual-use technology] information and use it against us’ (Packham, 2019).

Ethics are another potential issue of concern stemming from research collaboration with China. For example, media reporting has raised questions around whether collaborative research between Australian universities and Chinese entities might have facilitated human rights abuses in China, such as the mass surveillance of its Turkic Muslim population in the northwest province of Xinjiang, who are being subjected to mass internment and forcible indoctrination. Two Australian universities – the University of Technology Sydney and Curtin University - recently announced they would undertake reviews of collaborative activities with Chinese entities in response to such concerns (ABC, 2019).

A further challenge facing Australia-China research collaboration is deteriorating conditions for academic inquiry in China due to an increasingly repressive political regime. These are overviewed by Kennedy (2019). The first is that the Chinese government’s increasingly stringent implementation of ‘cyber-sovereignty’ policy has impeded access to foreign web-based services. This in turn prevents usage of web applications that assist search for literature and file-sharing, in addition to rapid dissemination and discussion of findings. Calls by Chinese scientists to relax such restrictions have themselves been censored.

The second is an intensifying campaign of ideological and political control over universities by the Chinese Communist Party (CCP), to the detriment of focusing on knowledge creation. In its attempts to ensure universities’ political and ideological alignment, the CCP has dramatically stepped up its control over university affairs such as teaching content, funding and student admissions. Illustrative of this is recent reporting that identifies the political stances of teaching staff at China’s prestigious Tsinghua University as a ‘top priority’ in performance evaluations. Other examples of party-state influence over universities include the placement of the National Science Foundation of China under the Ministry of Science and Technology’s supervision, the leadership overhaul of seven of China’s top universities and the suspension or dismissal of academics who have criticised China's administration.

The third is that despite ambitious efforts – such as the controversial Thousand Talents program that aims to attract high performing Chinese scholars currently overseas to return home – China still experiences considerable difficulty in attracting and retaining top talent. For example, Kennedy (2019) notes:

> In 2015, 85 percent of Chinese students who had received a PhD in a science or engineering field from a US university five years earlier were still in the US.

He further observes that multiple high-profile researchers who had returned to China subsequently left. Kennedy posits that this problem is exacerbated by the previous two trends, which limit the attractiveness of China’s environment to researchers who have previously worked in less politically restrictive countries.

A final factor with potential to negatively impact on Australia-China collaboration stems from the utility that Chinese researchers derive from working with their Australian counterparts. Collaboration is a mutual endeavour with both sides needing to see value from joint work. This in turn implies that Australian universities must host leaders in their fields. Yet the ability of Australia to produce, attract and retain the best researchers, particularly those in science and technology, has been stifled by funding pressures on universities (Nogrady, 2018).
In the most recent example, the Australian Government’s 2019-20 Budget saw a $345.2

million reduction in funding for research block grants, $6.7 million for the ARC and $6.6 million for the National Collaborative Research Infrastructure Strategy in the four years to 2022 (Bolton, 2019). This could result in a markedly disadvantageous paradox wherein Australian researchers are increasingly incentivised to look abroad for collaboration partners to stay at the leading edge of knowledge creation, while simultaneously becoming less attractive as collaboration partners themselves.

To date Australian highest-ranked universities have largely been able to retain their attractiveness for collaboration by developing alternative income streams, most notably by enrolling overseas students, and particularly those from China. For example, Australia only has one university in the world's top 50 for engineering/technology and computer science, the University of New South Wales (UNSW) (ARWU, 2016). By 2018, UNSW was earning more than $800 million in revenue from overseas students, with those from China accounting for 74 percent of that. This was in the context of total spending of nearly $2.5 billion. In other words, Chinese students underwrote nearly one-quarter of UNSW's budget (Goodwin, 2019). The potential for Australian universities to maintain their standing as a collaboration partner through such means is questionable.

6. Conclusion

Collaborating with international partners to create knowledge is one of the ways that Australia stays at the international technology frontier and maintains its high-income status, despite its limited scale and resources. The preliminary analysis conducted in this paper finds that while collaboration with traditional partners such as the US remains strong, there has been a rapid and dramatic rise in both the quantity and quality of knowledge created in collaboration with China. It is expected that this year or next China will overtake the US to become Australia's leading international collaborator in terms of the total number of co-authored articles produced. Research subject area analysis also reveals collaboration with China and the US to be highly complementary being weighted towards the physical and life sciences, respectively. In certain subject areas such as engineering China is now a vital research partner accounting for more than half of Australia's total output of highly-cited publications. Yet despite the growing importance of collaboration with China for Australia, the future trajectory is uncertain, reflecting concerns around the security and ethical outcomes of joint research, the erosion of academic freedom in China and funding pressures on Australian universities.

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