# Returns on Investment: Considerations on Publicly Funded ICT Research and Impact Assessment

Annette Lois McLeod

ORCID: 0000-0001-8179-5076

*Submitted in total fulfilment of the requirements of the degree of*

**Doctor of Philosophy**

November 2016

Department of Electrical and Electronic Engineering

The University of Melbourne

# Abstract

In recent years there have been increasing calls for research to justify public funding by demonstrating how it benefits wider society. This has led to an accompanying search for meaningful metrics and indicators of impact for use in assessment, decision making and policy and program formulation.

This thesis examines issues to be considered when attempting to determine the impact of publicly funded research, with particular reference to information and communications technology (ICT). Drawing on many disciplines and often having its biggest impacts outside the corresponding industrial sector, ICT provides a useful lens through which to examine issues surrounding impact and its assessment.

Before exploring the idea of impact itself, the question of why governments should support research, particularly ICT research, is looked at, from wide-ranging economic benefits to national security. The main types of research impact are identified, along with common difficulties that arise when attempting to assess them.

For research to have impact it predominantly needs the intervention of other parties, such that the question arises as to just how much control researchers actually have over the ability of their research to have impact. In which case, should we be more interested in assessing the potential for impact? If so, what are appropriate indicators and metrics to use? Where does peer review, the traditional method of assessing research, fit in this framework?

For government funded research to have an impact, it must first be clear about what it is trying to achieve before determining what indicators are best suited for the demonstration of success. The thesis concludes by posing some questions that should be considered when funding programs are being constructed.

Included in the thesis are three case studies, examining models for having impact via doctoral training, trans-disciplinary research and sectorial engagement within the Australian higher education sector.

# Declaration

This is to certify that:

- This thesis comprises only my original work towards the degree of Doctor of Philosophy;
- Due acknowledgement has been made in the text to all other material used;
- The thesis is less than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

.

………………………………………………………………………………..

Annette Lois McLeod

22nd November 2016
………………………………………………………………………………..

Date

# Acknowledgements

An endeavour such as the production of a research thesis is only possible with the support of many people. First and foremost, my gratitude must go to my primary supervisor, Prof Rob Evans, who first planted the seed and never lost faith. Good advice and reassurance at just the right times makes all the difference. Thank you also to my co-supervisor, Prof Iven Mareels, and committee chair, Prof Chris Leckie, for their insightful comments and continuous encouragement.

To my colleagues, past and present, at the Centre for Neural Engineering, the Defence Science Institute, NICTA Victoria Research Lab and the Department of Electrical and Electronic Engineering, thank you for your support, your wisdom, your research experience, your friendship and your willingness to let me think out loud. Special thanks must go to Jan, Luan, Angie, Nancy, Ansonne and Dom.

To family and friends who made sure I had the occasional proper meal and time away from the keyboard, thank you for being there and never questioning my decision to take on this mammoth task.

Finally, I am indebted to those whose work I have drawn on in formulating my ideas. We are all able to see further thanks to the giants whose shoulders we stand on.

# Returns on Investment: Considerations on Publicly Funded ICT Research and Impact Assessment

## Table of Contents

# List of Figures and Tables

# List of Abbreviations & Acronyms

| | |
|---|---|
| AAS | Australian Academy of Science |
| ABS | Australian Bureau of Statistics |
| ACM | Association for Computing Machinery |
| ACT | Australian Capital Territory |
| AFOSR | Air Force Office of Scientific Research (USA) |
| ANSTO | Australian Nuclear Science Technology Organisation |
| ANU | Australian National University |
| ANZSIC | Australia and New Zealand Standard Industrial Classification |
| ANZSRC | Australia and New Zealand Standard Research Classification |
| ARC | Australian Research Council |
| ASIC | Australian Securities and Investment Council |
| ARPANET | Advanced Research Projects Agency Network (USA) |
| ATAR | Australian Tertiary Admission Rank |
| ATSE | Australian Academy of Technological Sciences and Engineering |
| AusHSI | Australian Centre for Health Services Innovation |
| CERN | European Organization for Nuclear Research (Conseil Européen pour la Recherche Nucléaire) |
| CfNE | Centre for Neural Engineering, University of Melbourne |
| CMI | Cambridge-MIT Institute (UK) |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation (Australia) |
| DARPA | Defense Advanced Research Projects Agency (USA) |
| DoD | Department of Defense (USA) |
| DOI | Digital Object Identifier |
| DSI | Defence Science Institute |
| DST group | Defence Science and Technology (formerly DSTO) |
| DSTO | Defence Science and Technology Organisation (Australia) |
| EPO | European Patent Office |
| FOSH | Free and Open Source Hardware |
| GDP | Gross Domestic Product |
| GERD | Gross Domestic Expenditure on R&D |

| | |
|---|---|
| GRDC | Grains Research and Development Corporation (Australia) |
| HSC | Higher School Certificate |
| ICT | Information and Communication Technologies |
| IEEE | Institute of Electrical and Electronic Engineers |
| IP | Intellectual Property |
| IT | Information Technology |
| JIF | Journal Impact Factor |
| KIC | Knowledge Integration Community |
| KPI | Key Performance Indicator |
| MIT | Massachusetts Institute of Technology (USA) |
| MNC | Multi-National Corporation |
| NFP | Not-For-Profit |
| NGO | Non-Governmental Organisation |
| NHMRC | National Health and Medical Research Council (Australia) |
| NICTA | National ICT Australia Ltd |
| NICTA VRL | National ICT Australia Ltd Victoria Research Laboratory |
| NIMBios | National Institute for Mathematical and Biological Synthesis |
| NSF | National Science Foundation (USA) |
| NSW | New South Wales |
| OECD | Organisation for Economic Co-operation and Development |
| PFRA | Publicly Funded Research Agency |
| PhD | Doctor of Philosophy |
| R&D | Research and Development |
| RAE | Research Assessment Exercise (UK) |
| REF | Research Excellence Framework (UK) |
| RHD | Research Higher Degree |
| RIBG | Research Infrastructure Block Grants |
| RIRDC | Rural Industries and Development Corporation |
| SME | Small to Medium Enterprise |
| STEM | Science, Technology, Engineering and Mathematics |
| UNSW | University of New South Wales |
| USPTO | United States Patent and Trademark Office |
| WIPO | World Intellectual Property Organization |

# Chapter 1: Introduction

*"Algorithmic and statistical refinement matters not a jot if the metrics in question do not measure what they claim to measure or are applied inappropriately: fitness for purpose needs to be demonstrated, not presumed."*

- Blaise Cronin & Cassidy R Sugimoto, Beyond Bibliometrics Harnessing Multidimensional Indicators of Scholarly Impact, 2014

The World Bank (2016) estimates that in 2013, 1.7% of global gross domestic product was spent on research and development. In OECD countries, R&D provides employment for more than nine million people, with 28.35% of the R&D expenditure taking place across that grouping of countries being funded by their governments (OECD, 2016). This represents significant national investments in what is essentially a long-term, high-risk activity. As with any expenditure, governments must be able to justify this spending of citizens' money.

Globally there is a movement towards using examination of the impact of research on wider society as a means of justifying public funding and to identify ways of improving the diffusion and use of research outcomes. This is following on from recent developments in research quality assessment and thus far is following a similar trajectory.

The notion of research impact assessment in this context is currently unfixed. While there is some consensus amongst policy makers concerning the general definition of research impact, there is considerable ongoing discussion regarding the particulars and how you first relate impact to specific research activities and then assess these impacts. Despite numerous unanswered questions, national research impact assessment exercises are being introduced in a number of countries, along with the consideration of impact as part of funding applications. The inclusion of impact in these processes requires researchers, managers and funders to identify how their work fits within a wider societal context. For many, particularly those working at the more fundamental end of the spectrum, this is a significant change.

This thesis examines issues surrounding the assessment of research impact, with particular emphasis on publicly funded information and communication technologies (ICT) research within the Australian context. Practitioners of ICT research come from a wide variety of discipline backgrounds and work at all points along the R&D continuum. With a frequent focus on the development of platform technologies, ICT is also considered an *enabling* technology, one that supports further research and development breakthroughs in other disciplines. Given these characteristics, it is not unreasonable to suggest that many questions regarding the assessment of research impact will manifest themselves within the ICT field. While this thesis aims to view research impact predominantly through the lens of ICT, the ubiquity of this technology across all facets of society necessitates drawing on work examining other fields. The concept of impact has been examined by the medical research community for a number of years, providing valuable insights and the emerging convergence of biological, physical and engineering sciences continues to widen the sphere of influence of ICT in our lives.

To be able to undertake a meaningful impact assessment of publicly funded research there are a number of questions which need to be considered. While this thesis does not presume to have answers, it does aim to increase awareness of these issues, and to promote care and caution when interpreting and using the results of assessment exercises.

Administrative efficiency, ease of comparison and political constraints typically result in a desire for simple metrics which support data-driven decision making. Research is a complex, multi-faceted enterprise, with myriad impacts and varied ways of achieving that impact. Like quality, impact has a subjective component, with context playing a large role. For these reasons, while particular aspects of impact can be measured, its assessment is likely to always require human judgement. This judgement should always begin from the perspective of why the research is being funded - what is the government or a particular program attempting to achieve? Unless they are 'mission directed', publicly funded research programs tend to have broad policy-driven behavioural goals such as encouraging collaboration or increasing training. Yet, most impact assessment programs are focused on the impact of research outputs, rather than the general policy-related impacts. Research impacts also make themselves evident in different ways, and it must be recognised that at times, the ways in which impact occurs can be mutually exclusive. Choices may need to be made between economic and environmental impact, between social and academic impact. Clear objectives make these choices easier and guide the selection of appropriate assessment methods and metrics.

The differing ways in which research has impact means there are many ways in which impact components can be measured and hence overall impact assessed. A number of the common metrics proposed are examined here, with regards to their advantages, limitations and relationship to actual impact. It is evident there is no 'one size fits' all metric and a suite of metrics and indicators must be assembled so assessors can choose those deemed most suitable. Often, these metrics will primarily be useful as supporting evidence for complex, nuanced narratives.

Research impact assessment is currently being targeted at researchers themselves and the institutions where they undertake their work. But this assumes that, in addition to where research happens, it is also where translation and implementation happens. The reality is that research impact results from the contributions of a variety of actors both within and outside the research and development community. In which case, how will assessing research impact at the source of the idea provide us with meaningful information in regard to improving the likelihood of research achieving its full potential within society? Or is the drive for assessment concerned more with holding researchers accountable, rather than with improving the return on this major public investment? The answer to this question is vital in determining how best to assess research impact and how we then use the results of those assessments.

The thesis shall begin by looking at the difficulties in defining ICT research (Chapter 2) before examining some of the reasons why public funding of research, and in particular ICT research, is considered necessary (Chapter 3), such as

- Productivity and economic growth;
- The development of human capital and absorptive capacity; and
- National security.

We then go on to discuss impact itself, including the broad areas in which research is typically expected to have impact and introduce some of the difficulties impinging on our ability to easily assess impact (Chapter 4). These difficulties include

- Identifying appropriate time frames;
- The potential for competing areas of impact;
- Delineating between correlation and causation; and
- Determining who the results should be attributed to.

Chapter 5 examines some of the language that is commonly used when discussing impact assessment and the subtle differences between key terms. Factors which can influence the ability of a piece of research to have impact will then be discussed, leading to the question of how much influence researchers themselves have over the likelihood of their research having impact (Chapter 6). Chapter 6 also introduces the first case study, looking at a collaborative, sectorial approach to increasing university-industry-government interactions as a way of encouraging eventual research impact (6.5.1 – DSI).

Having raised the question of potential for impact in Chapter 6, Chapter 7 further examines some common metrics and indicators that have been proposed for use in impact assessment such as

- Bibliometrics, scientometrics and citation analysis;

- Patenting, software and licencing income;
- Company and job creation; and
- Altmetrics.

Two further case studies are included here, one concerned with the effect of multi-disciplinary research on publishing practices (7.1.1 – CfNE) and the other concerned with the training of doctoral students and their subsequent employment patterns (7.4.1 – NICTA VRL).

Chapter 8 looks at some of the difficulties associated with undertaking assessment impacts, such as linking research and impacts, while Chapter 9 considers the role of peer assessment. This is then followed by a short discussion of the importance of including impact assessment considerations from the earliest stages of program development (Chapter 10).

The pathway from research to implementation and ultimately impact is complex, multi-faceted and non-linear, involving multiple actors, competing agendas, tangential influences, detours and side-roads. To expect that any method of assessing research impact will be otherwise is to court disappointment.

# Chapter 2: What is ICT Research?

Australia invests more in ICT related research and development than any other field. The year 2013/14 saw Australian business spend $7.7 billion on information and computing science and technology R&D, 41% of the total business R&D expenditure for the year (Australian Bureau of Statistics, 2015c). The following year, government and not for profits spent $407 million, or 40% of their total R& D spend in these two fields of research (Australian Bureau of Statistics, 2016). Similar amounts were spent on engineering R&D, of which a significant portion would relate to ICT. Representing a significant national investment, in recent decades ICT has transformed society and economies, providing the tools which underpin many of our daily activities. The question of why investment in ICT R&D is considered necessary shall be examined further in Chapter 3, but first we must determine what ICT actually is.

## 2.1 The Science of ICT – A Gathering of Disciplines

ICT. Information and Communications Technology. Many people are familiar with the term. Even more are well acquainted with its shorter cousin – IT. But what actually is ICT? For a term in such common use the answer can be surprisingly difficult to find. When attempting to define ICT research this difficulty only increases.

Wikipedia (2012) has previously defined ICT as

> *" … a more general term that stresses the role of unified communications and the integration of telecommunications (telephone lines and wireless signals), computers, middleware as well as necessary software, storage- and audio-visual systems, which enable users to create, access, store, transmit, and manipulate information. In other words, ICT consists of IT as well as telecommunication, broadcast media, all types of audio and video*

*processing and transmission and network based control and monitoring functions."* [1]

A more recent definition from Wikipedia (2016) reads

*"… an extended term for information technology (IT) which stresses the role of unified communications and the integration of telecommunications (telephone lines and wireless signals), computers as well as necessary enterprise software, middleware, storage, and audio-visual systems, which enable users to access, store, transmit, and manipulate information.*

*The term ICT is also used to refer to the convergence of audio-visual and telephone networks with computer networks through a single cabling or link system. …*

*However, ICT has no universal definition, as "the concepts, methods and applications involved in ICT are constantly evolving on an almost daily basis." The broadness of ICT covers any product that will store, retrieve, manipulate, transmit or receive information electronically in a digital form, e.g. personal computers, digital television, email, robots."*[2]

and includes acknowledgement that the definition is not necessarily fixed, nor agreed upon.

The Oxford Dictionary of English considers ICT an abbreviation for

*"information and computing technology"* (Oxford Dictionary of English, 2005)

with the definition for information technology being

[1] https://en.wikipedia.org/wiki/Information_and_communications_technology; accessed 3rd March 2012

[2] https://en.wikipedia.org/wiki/Information_and_communications_technology; accessed 29th August 2016

> *"the study or use of systems (especially computers and telecommunications) for storing, retrieving, and sending information"*
> (Oxford Dictionary of English, 2005)

Zuppo (2012) notes the precise meaning of the term ICT varies depending on the context in which it is being used, although there would appear to be a common theme which is centred on the various devices and forms of infrastructure that support digital methods of transferring information internationally.

For most people, information technology conjures images of computers, software and the internet, while the addition of communication brings in telephony and associated technologies such as optical fibre networks. But there is much more to this story and the notion of ICT as a discrete research entity may be hard to sustain. Practitioners in ICT bring many different disciplines to a wide variety of applications and while governments often talk about ICT as a distinct economic sector with a corresponding research sector, identifying the full extent of a country's research in ICT can be difficult due to the wide discipline base.

In Australia, statistical data relating to research and development (R&D) is categorized according to the Australian and New Zealand Standard Research Classification (ANZSRC) which allocates each R&D activity an activity type (for example, pure basic research or applied research), a field of research (or hierarchical discipline category) and a socio-economic objective (or purpose or area of application) (Australian Bureau of Statistics, 2008).

Information and Computing Sciences are given top-level research field recognition (Division) within the ANZSRC, on a par with broad groupings such as Mathematical Sciences, Earth Sciences, Engineering and Health and Biomedical Sciences. As a hierarchical structure, it is when one looks at the next level of classification (Groups) and the Fields of Research they are comprised of, that identifying the broad parameters of ICT research activity becomes more problematic (Table 1.).

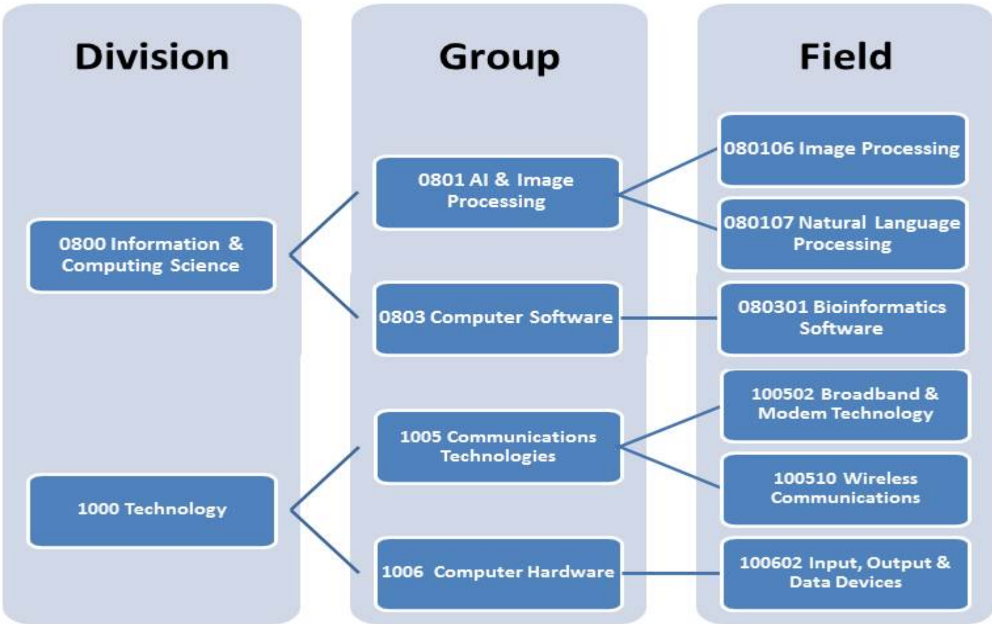


**Figure 1: Examples from ANZSRC Hierarchical Field of Research Classification (*Australian Bureau of Statistics, 2008)***

The Information and Computing Sciences Division includes the Groups of Artificial Intelligence and Image Processing, Computation Theory and Mathematics, Computer Software, Data Format, Distributed Computing, Information Systems, Library and Information Studies, and Other Information and Computing Sciences. With the possible exception of some streams of Library and Information Studies, all undoubtedly would be considered ICT research. To find many of the other research fields traditionally associated with the communications component of ICT, one has to go the Technology Division, and from there to the Communications Technology Group. It is here that disciplines such as Broadband and Modem Technology, Optical Fibre Communications, Computer Communications Networks and Data Communications are to be found. (Interestingly, while optical fibre communications are considered as a Communications Technology, photonics, optoelectronics and optical communications are not). Computer Hardware is also included within the Technology Division, while integrated circuits not intended for use in actual computers are included within the Electrical and Electronic Engineering Group of the Engineering Division. This split between dedicated and integrated computing equipment may be a reflection of the definitions traditionally used for the IT industry sector. Looking at some of the exclusions detailed for the Information and Computing Sciences division is instructive in itself (Table 2.).

| Excluded Topic | Allocated Division | Allocated Group |
|---|---|---|
| Mathematics not associated with computer science | 01 Mathematical Sciences | various |
| Cheminformatics | 03 Chemical Sciences | 0304 Medicinal & Biomolecular Chemistry |
| Bioinformatics | 06 Biological Sciences | 0601 Biochemistry & Cell Biology |
| Mechatronics for automotive engineering | 09 Engineering | 0902 Automotive Engineering |
| Signal processing & non-manufacturing robotics | 09 Engineering | 0906 Electrical & Electronic Engineering |
| Geospatial information systems | 09 Engineering | 0909 Geomatic Engineering |
| Manufacturing robotics, mechatronics (excluding automotive applications) and CAD/CAM systems | 09 Engineering | 0910 Manufacturing Engineering |
| Computer perception, memory and attention | 17 Psychology & Cognitive Sciences | 1702 Cognitive Sciences |
| Computational linguistics | 20 Language, Communication & Culture | 2004 Linguistics |
| Archival, repository and related studies | 21 History & Archaeology | 2102 Curatorial and Related Studies |

**Table 1: Noted Exclusions from the ANZSRC Information & Computing Sciences Division (Source: ABS, 2008)**

It should be noted that the development of any computer software, other than mathematics and bioinformatics software, is classified under the Group to which it is being applied. For example, research and development of computer models for use in atmospheric research are classified within the Earth Sciences division. This suggests that ICT is considered largely to be an enabling technology, one that supports other areas of research and applications. We shall look at one of the implications of this view later in this chapter.

The application of the ANZSRC codes determines the official statistics regarding Australia's investment in research, but the distribution of relevant disciplines and fields of research within the hierarchy as detailed above means that forming an accurate picture of the overall extent of ICT research in the country is quite difficult. A significant component of the nation's ICT research is likely to be classified as research within the wider application area. While funding bodies such as the Australian Research Council collect information at the six digit Field level in relation to grants they fund, the Australian Bureau of Statistics limits its collection and analysis to the Division level, effectively ensuring that a significant portion of ICT research is hidden from view.

Once research fields have been identified, the activity is then allocated to one or more socio-economic objectives. There is an Information and Communications Division, including Groups such as Communication Networks and Services, Computer Software and Services, Information Services and Media Services. However, in the absence of a large technical manufacturing industry and with the new ICT emerging from convergence with other disciplines, most ICT research undertaken in Australia is applied in other socio-economic objectives such as Health, Manufacturing, Transport and the Environment. This is not unique to ICT and nor is it surprising given the enabling nature of the technology.

Similar to Australia, the United States National Science Foundation (NSF) does not recognize ICT as a discrete research grouping. Many of the research disciplines contributing to ICT are found under the Electrical, Communications and Cybersystems Organisation of the Directorate of Engineering, the Directorate of Computer & Information Science & Engineering or the Directorate of Mathematical & Physical Sciences (National Science Foundation, 2012). The Natural Science and Research Council of Canada funds most ICT related research within the two evaluation groups of Computer Science and Electrical & Computer Engineering. (Natural Science and Research Council of Canada, 2012). Research Councils UK's Engineering and Physical Sciences Research Council recognises ICT as one of its four research themes, along with Physical Sciences, Mathematical Sciences and Engineering. The Council defines the theme as including research in the areas of computer science, user-interface technologies, communications, electronics and photonics with research under the theme relating to challenge areas of Digital Economy, Energy, Healthcare Technologies and Manufacturing the Future (Engineering & Physical Sciences Research Council, 2012).

From a discipline perspective, research areas within the United Kingdom's ICT theme are diverse, including areas such as natural language processing, optoelectronic devices, microelectronic design, software engineering, radio-frequency & microwave devices, artificial intelligence, human-computer interfaces, biological informatics, digital signal processing and image and vision computing. While there are a small number of disciplines within other themes (for example, robotics and medical imaging in Engineering, quantum optics and information in Physical Sciences) the Council is one of the first major public funding bodies to attempt to bring all the ICT related disciplines together for funding programs.

The European Commission included ICT as a theme within the 7$^{th}$ Framework Program of research funding with areas such as communication networks, embedded computing, nanoelectronics and technologies for audiovisual content (European Commission, 2012). While the Commission has specifically mentioned network and service infrastructure and security, performance and reliability of electronic systems and components, personalized ICT systems and digital content management as priority areas, the ICT research being focused on as part of this framework program is relatively narrow compared to most national research funding instruments.

For economic analysis and comparison the OECD has defined the ICT industrial sector as

> *"The production (goods and services) of a candidate industry must primarily be intended to fulfill or enable the function of information processing and communication by electronic means, including transmission and display"* (OECD 2007).

Industries that meet this requirement are:

- Manufacture of electronic components and boards, computers and peripheral equipment, communication equipment, consumer electronics and magnetic and optical media;
- Wholesale of computers, computer peripheral equipment and software, electronic and telecommunications equipment and parts;
- Software publishing;
- Wired, wireless, satellite and other telecommunications;
- Computer programming, consultancy, facilities management and related activities;
- Data processing, hosting and related activities; web portals; and
- Repair of computers, peripherals and communication equipment (OECD 2007).

These include industries aligning strongly with the ANZSRC SEO application of ICT mentioned earlier. In their 2015 study, Basole, Park and Barnett identify fifty-eight four-digit *Standard Industrial Classification* codes as being part of the ICT ecosystem, distributed across five sectors: hardware components, hardware equipment, software, telecommunications and media. (It should be noted that included in the media sector were traditional production and distribution activities such as publishing, broadcast and advertising areas). However, it should be obvious that a significant portion of ICT research and industrial activity is occurring outside these sectors.

The fact there is not necessarily a direct correlation between a research field and an industry sector is not unique to ICT. After all, there is a well-defined defence sector and the corresponding defence research occurs across a vast number of highly disparate disciplines. Similarly, agricultural research is underpinned by a wide range of disparate disciplines. However, in these situations, governments who fund defence or agricultural research generally see the outcomes put to use in those sectors in the first instance. Much ICT research, particularly that which is publicly funded, is not put to use within the ICT sector, but in others such as manufacturing, health and agriculture, reinforcing the view of ICT as an enabling and platform technology and furthering the potential for impact. This suggests the outcomes and impacts of ICT research may be attributed to the sectors in which it is applied, especially where the contribution of ICT research and development to the economy or quality of life is understated, or just too difficult to identify.

For example, the Australian mining industry is recognised internationally as being highly innovative. Laser scanning, wireless network components for reliability in harsh conditions, planning and operations software, training simulators and automated positioning systems have all had a significant impact on productivity and safety within the industry. At their core, these all require the application of innovations developed in ICT to issues within the industry and many will also require further ICT innovation to solve specific mining problems. This sets up a cycle where ICT innovation drives industry innovation while industry problems drive ICT innovation. Productivity gains arising from this type of innovation cycle will generally be attributed to the industry applying the innovation: is Australia's reputation in mining innovation actually the result of underlying ICT innovation strengths?

## 2.3 The New ICT – A Trans-Disciplinary View

*"The end result of this culture of convergence can be transformational, calling for disruptive change in technology and capability…"*

– WS Grundfest, E Lai, CM Peterson & KE Friedl, Promoting Innovation and Convergence in Military Medicine: Technology-Inspired Problem Solving, 2012

In 2011, a group of senior faculty at the Massachusetts Institute of Technology (MIT) defined convergence as different fields of study coming together to create new pathways and opportunities, through collaboration and the integration of different (and possibly contradictory) methods and approaches (MIT, 2011). Two years previously, in their report A New Biology for the 21st Century (2009), the National Research Council (USA) noted that in order to address a broad range of scientific and societal problems it was not only necessary to re-integrate biology's many sub-disciplines, but to also integrate physicists, chemists, computer scientists, engineers and mathematicians into biology. In his 2014 Presidential address to the American Association for the Advancement of Science, Phillip Sharp quoted MIT Emeritus President Susan Hockfield as saying

> *"Physicists gave engineers the electron, and they created the IT revolution. Biologists gave engineers the gene, and together they will create the future."* (Sharp, 2014).

It has been suggested by Ross (2015) that the single challenge of understanding information processing is at the core of many of the most complex issues we face as a society, whether this information processing is being carried out by our brains, the universe, DNA or computers using silicon-based technology. If this is the case, then convergence between biology and the tools and techniques developed within the ICT community would appear to be inevitable as we seek to further our understanding.

Convergence is more than just collaboration between disparate disciplines. It also involves the application of physical sciences and engineering knowledge, tools, techniques, approaches and ways of thinking to biomedical and life sciences problems, and vice versa. At its heart, there is trans- and multi-disciplinary collaboration right from the beginning where all collaborators share a common language and reference points (Sharp & Langer, 2011).

Convergence is thought to drive innovation, provide stimulation for the translation of basic research and create a framework for tackling those major challenges which tend to sit at the intersection of multiple disciplines (National Research Council, 2014). Sharp and Langer (2011) also posit that convergence is more than just the intersection of disciplines, but that from this work, new disciplines will emerge (for example, tissue engineering, nanobiotechnology, nanoinformatics).

Waltman, van Raan and Smart (2014) estimate that during the first decade of the twenty-first century, 10% of engineering and physical sciences and health and life sciences research publications recorded in the *World of Science* database were reporting on work at the interface between these two broad groupings. They conclude there are some health and life sciences fields where advances are driven in a significant part by advances in engineering and the physical sciences and point to increases in computing power as playing an essential role in the growth in bioinformatics research seen over the period. Another example of this can be seen in the advances in implants and bionics made possible due to advances in microelectronics and materials engineering.

Information and communications technology exists as a grouping of disciplines based on broad and often ill-defined application areas. These application areas are then applied across additional disciplines and applications. Is a bioinformatician who comes up with new search methods and software to better identify gene sequences associated with a particular mental disorder undertaking research in bioinformatics, neuroscience, software engineering or genomics? The answer is likely to be all four.

Disciplinary specialisation in science is thought to have arisen in the nineteenth century, and one characteristic of modern science is an openness to recognising new and emerging disciplines (Stichweh, 2015), such that there has been increased specialisation. Disciplines provide a framework for organising the transmission and communication of knowledge, allowing us to recognise the body of knowledge that is relevant to a particular area. They are the organising structures for our major knowledge producers and institutions of learning – universities. Academic journals and conferences are largely organised by discipline, making it easier for practitioners to find the knowledge of use to them. The rise of convergence may see a move towards specialised generalists, those who have deep discipline knowledge across more than one highly disparate discipline. It is likely to provide a significant challenge to university management, in the ways that teaching is organised, supervisory lines are structured and resources are allocated.

Assessing research in the convergence space will bring its own challenges. Disciplines have accepted methodologies and epistemologies arising from their particular theoretical paradigms and the criteria used to determine quality can be contradictory when applied on a discipline basis (Belcher, Rasmussen, Kemshaw & Zornes, 2016). However, as noted by Gooch, Vasalou and Benton (2016), inter-disciplinary and cross-sectoral collaborators bring differing viewpoints about impact to the table and can lead to impact being created on a greater number of levels. The disparate nature of stakeholders and practitioners has the potential to bring conflicting views in regards to what impacts are desirable. Jahn and Keil (2015) suggest a framework for assessing the quality of transdisciplinary research based on the quality of the research problem, the research process and the research results. Given that much research of this type emergences in response to specific issues, it may be that while the traditional quality of research is hard to assess, impact may be relatively simple: how have you progressed towards a solution to the problem?

# Chapter 3: Why Should Governments Fund ICT Research?

*"The Sovereign has the duty to … maintain certain public works and certain public institutions, which can never be for the interest of any individual … because the profit could never repay the expense to any individual … though it may frequently do much more than repay it to a great society."*

- Adam Smith, An Inquiry into the Nature and Causes of the Wealth of Nations, 1776

## 3.1: The Pursuit of Knowledge

Possibly the purest of motives for government funding of any research is the pursuit of knowledge for its own sake. Human curiosity is a powerful motivator for many who take up careers in research. There is a tacit belief that attempting to answer the fundamental question of *why is it so?* is a noble undertaking and one that should be supported to some extent by society. However, when framed as a stark choice between building a hospital to save lives right now or undertaking research that may possibly lead to something that might help us to save lives in the future, supporting research can seem like an indulgence, especially when resources are limited.

ICT research can be an expensive undertaking. The Office of the Chief Scientist (2014) found Australian ICT research has the highest cost per publication of all STEM fields. When coupled with low average citation rates, this suggests Australia does not get value for money in the pursuit of knowledge in ICT compared to other areas it funds. The report does acknowledge that the cost per publication does not take into account the differences in costs in undertaking research in different fields, especially infrastructure (as one would expect, medicine also has a high cost per publication) (Office of the Chief

Scientist, 2014). But of concern for those in the ICT research community, bibliometric data was obtained from Thompson Reuters' *Incites* (*Web of Science* data) and Elsevier's *Scopus*, with discipline comparisons being made on the basis of this data.

Historically, conferences have been very important in the fields which contribute to ICT. For example, while recognising that journals have a role, Franceschet (2010) notes that in computer science they are not necessarily more prestigious than the conferences and that outputs such as software can be just as important as research publications. This makes computer science different to many other academic disciplines. While *Scopus* includes many of the peak body's conferences (Association for Computing Machinery - ACM) and an increasing number of books, computer scientists in the past have tended to be highly critical of the *Web of Science* both for its failure to cover highly influential (and cited) conferences and books and its general failures regarding computer science as discipline:

> *"The database has little understanding of CS* [computer science]*. … the cruellest comparison is with Citeseer, whose Most Cited list includes many publications familiar to all computer scientists; it has not a single entry in common with the ISI* [Web of Science] *list.*" (Meyer, Choppy, Staunstrup & van Leeuwen, 2009)

For computer science researchers, artefacts such as software and code are also an important component of their research output and any assessment which ignores this is likely to underestimate activity. Similarly, for engineers the production of prototypes, patents and practice guidelines are common outputs which are usually not considered in standard assessment exercises. Citation analysis and some of its limitations shall be discussed in more detail later, but suffice to say that from the perspectives of government, even if they purely fund research for its own sake, they will still be looking for maximum return on investment. While this thesis is more concerned with assessing the benefit side of that proposition, determining the cost side per output may also be controversial, given that outputs are not necessarily comparable between disciplines and there are difficulties in determining the full extent of ICT research.

As we shall see in the next chapter, regardless of motive, the pursuit of knowledge by society is believed to have important spillover effects that support economic goals in addition to solving definable issues.

## 3.2: The Link Between Research, Innovation and Productivity

*"Scientific discovery is first and foremost an expression of the relentless human search to know more about the world but it is also an enormous strength for a modern economy"*

– George Osborne, UK Chancellor of the Exchequer, Spending Round 2013 Statement to Parliament, 2013

Research is, by its very nature, a high-risk activity: there is never any guarantee you will achieve the result you are hoping for. Indeed, it is not even strictly necessary to have a defined goal when embarking on a research question. Long time periods and significant amounts of money can be invested in pursuit of goals that, in hindsight, are improbable or even impossible. The result of this is that industry, quite understandably, is reluctant to undertake research in areas other than the most applied. Products which are held up as exemplars of industrial innovation, such as the Apple iPhone and Google search, can be heavily reliant on publicly funded research (Mazzucato, 2013), with the nature of the innovation grounded in combining and exploiting a range of technologies.

The perceived market failure when it comes to research, particularly fundamental research, is generally accepted as a valid reason for the intervention of government through the supply of public funding. However, if we believe that investment in the pursuit of knowledge for its own sake is not worth sacrificing other societal needs for, why does this gap need to be filled?

### *3.2.1: Investing in Knowledge Capital for Innovation, Productivity and Economic Growth*

Just as the underlying purpose of all commercial enterprises is to provide a return to the owners, governments, at least in modern democracies, have an underlying purpose of making a return to their shareholders: the citizens. For commercial entities, returns are essentially in the form of profits, and increasing profit usually requires companies to either grow market share or become more efficient in the way they operate. Returns to citizens are more varied, but generally combine to provide an acceptable quality of life and the ability to go about their business without unnecessary interference. Governments do this by providing frameworks and services such as policing, health, education, regulation and infrastructure. Like companies, they can provide increased returns by doing things more efficiently.

The enjoyment of a reasonable quality of life by citizens contributes to national wellbeing and political stability. Government influences the quality of life in many ways, but providing the framework and conditions for a stable and flourishing economy is of most interest here. Economies are linked across the globe as never before and to maintain living standards, countries have to be competitive in the global market. Innovation and productivity are key drivers in maintaining competitiveness with the sciences making a significant contribution to the economy in many countries. In Australia, it is estimated that the last twenty years of advances in mathematics and the physical sciences, coupled with those made over the last thirty years in the biological sciences, is directly responsible for 14% of the country's economic activity at $185 billion per annum, contributes $84 billion a year in exports (or 25% of total goods and services exports) and directly employs around 10% of the workforce (Centre for International Economics, 2016a). Meanwhile in the United Kingdom, engineering alone is thought to account for 20% of annual gross value added (£280 billion) from a national investment of between £11.42 and £14.62 billion in research and training (Rosemberg, Simmonds, Potau, Farla, Sharp, Wain, Cassagneau-Francis & Kovacs, 2015). It is estimated graduates from Massachusetts Institute of Technology (MIT) are founders of more than 30,000 currently operating companies across the globe, employing 4.6 million people and generating revenues of USD$1.9 trillion, similar to the GDP of Russia (Roberts, Murray & Kim, 2015). The New Jersey life sciences industry is thought to contribute USD$33.5 billion to the state's GDP annually (Seneca, Lahr & Irving, 2014).

Clearly the research which underlies many of the activities in society makes a valuable contribution to national economies. However, it is not easy to decide where in the research/development/innovation/economy ecosystem governments should direct policy. Recent industry studies in Spain suggest that research has more effect on process innovation than development activities do, while when it comes to product innovation the reverse is true, particularly for those products which are new to the market (Barge-Gil & López, 2015). (It should be kept in mind that the boundary between research and development is not always easy to discern). Then there is the influence of factors outside research itself, such as capital availability. As we shall see, rather than providing clear direction, international comparisons of relevant metrics and indicators tend to reinforce the point that every economy is a function of the culture, resources and priorities of the underlying society (Table 2, Figure 2).

Of twenty-six countries compared, Japanese residents submit the most patent applications per head, while ranking 21st in terms of the number of scientific and technical publications produced. As Japan also ranks highest in the level of R&D expenditure by industry as a percentage of GDP (2.62%), with 75% of the country's R&D expenditure funded by industry, this should not be surprising. Industrial research is focused on gaining or maintaining competitive advantage so breakthroughs are less likely to enter the public domain via the academic literature and, as we shall see in Chapter 6.2, companies can practice defensive patenting as a business strategy. However, in GDP terms this high level of industry funded research and patenting may not have as large an effect as one would expect. Despite high-tech exports making up 20% of the country's manufacturing exports and 14% of total exports, they contribute only 2% to Japan's GDP. High tech exports make up a comparable portion of France's exports (26% of manufactured, 14% of total) yet contribute twice as much to

GDP (4%). Expenditure by French industry on R&D by GDP is half that of Japan (1.24%), accounting for slightly more than half of the country's total R&D spend (55%). In line with the increased role of government in R&D expenditure, French researchers produce more publications per 100,000 population (50 compared to 30), but while industry expenditure on R&D is relatively high, French patenting lags far behind the Japanese (23 compared to 213 per 100,000 population). In France, government funding of research coupled with more open dissemination of results is associated with a greater contribution to GDP compared to Japan.

The contribution of high tech exports to both GDP and as a percentage of total exports is greatest in Singapore (44% and 23% respectively), a middle ranking country in regards to industry expenditure on R&D (1.07% of GDP) and patenting (21 per 100,000). Of those compared, the only other country where high tech exports comprise more than 10% of GDP is Ireland, on 10.9% and it is one of the lowest countries for patenting (ranked 22 out of 26). Switzerland, another country where high tech exports contribute significantly to GDP (7.52%) produces more publications than any other country (124 per 100,000 population), but like Singapore, has low levels of patenting even though industry expenditure on R&D is a relatively high 1.8% of GDP. It may be that the extent of Switzerland's dominance of the global luxury and precision time piece market is a significant factor in the high export/low patent equation, given watchmaking's reliance on long-established technologies. In Ireland's case, a number of global software companies are structured such that much of their sales are routed through the country, which may contribute to high tech exports with low patenting. Meanwhile, Singapore may have found a niche as a manufacturer of high-tech goods developed elsewhere and has a thriving semi-conductor manufacturing industry whereby it exports large numbers of components.

Industry makes the same contribution to R&D expenditure in neighbours Finland and Sweden (2.01% of GDP). Publication and patenting rates are similar: 90 and 29 per 100,000 population in Finland; 99 and 24 per 100,000 in Sweden. Yet, at 6.5% of total exports, high tech exports contribute 3.05% to

Sweden's GDP while in Finland they only contribute 1.74%. It would appear the Finnish and Swedish economies are structured around different sectors.

China invests less in R&D than the United States (1.84% of GDP compared to 2.76%), and has less patenting and publication activity. This is not reflected in the relative contributions of technology exports to GDP. High tech exports contribute 6.14% to China's GDP but only 0.92% to that of the United States. The United Kingdom invests 1% of GDP less in R&D than the United States, with industry responsible for a third less than in the USA. Scientific productivity in terms of articles is similar, while patenting activity is far lower (23 compared to 90 per 100,000 population). At 2.59% the contribution of high tech manufacturing to the United Kingdom's GDP is almost three times that in the USA. Given the differences in geographic size, one would expect that the US economy includes a greater reliance on natural resources compared to the United Kingdom.

As a nation, Israel invests significantly in R&D – 3.97% of GDP, more than any other country compared – with most of that investment coming from Government (64%). Despite being middle ranking in terms of publications and patenting, that investment does appear to pay off in terms of GDP, with high tech exports contributing 3.58%.

Obviously patenting is not the only indicator of innovation activity and high tech exports are not the only contribution that ICT-related innovation will make to GDP. Nor is GDP without its limitations, especially when considering the quality of life for citizens. However, these comparisons do give us an indication of the complex environment that governments are attempting to manipulate.

| Country | R&D Expenditure as % of GDP[1] | % GERD by Industry[2] | Industry GERD as % GDP[2] | Science &Technology Articles per 100,000 Population[3] | Patent Apps by Residents per 100,000 Population[3] | High Tech Exports as % Manufactured Exports[1] | High Tech Exports as % Total Exports[4] | High Tech Exports as % GDP[4] |
|---|---|---|---|---|---|---|---|---|
| Australia | 2.39 | 61.91 | 1.39 | 89 | 13 | 12.91 | 1.46 | 0.31 |
| Austria | 2.77 | 47.36 | 1.40 | 60 | 25 | 13.72 | 7.41 | 3.97 |
| Brazil | 1.21 | | | 7 | 2 | | 3.12 | 0.39 |
| Canada | 1.79 | 46.45 | 0.75 | 83 | 13 | 14.06 | 4.38 | 1.32 |
| China | 1.84 | 74.60 | | 7 | 52 | 26.97 | 22.49 | 6.14 |
| Finland | 3.80 | 60.84 | 2.01 | 90 | 29 | 7.21 | 4.39 | 1.74 |
| France | 2.25 | 55.38 | 1.24 | 50 | 23 | 25.84 | 14.36 | 4.03 |
| Germany | 2.89 | 65.21 | 1.86 | 57 | 59 | 16.08 | 11.30 | 5.19 |
| Iceland | 2.60 | 38.77 | 0.77 | 80 | 10 | 8.07 | 1.29 | 0.73 |
| India | 0.81 | | | 2 | 1 | 22.42 | 2.77 | 0.68 |
| Ireland | 1.66 | 50.34 | 0.79 | 69 | 7 | 15.61 | 9.65 | 10.19 |
| Israel | 3.97 | 35.60 | 1.51 | 76 | 15 | 7.25 | 9.88 | 3.58 |
| Italy | 1.25 | 44.29 | 0.56 | 44 | 14 | 16.78 | 4.66 | 1.32 |
| Japan | 3.39 | 75.48 | 2.62 | 37 | 213 | 20.41 | 14.11 | 2.07 |

| Country | R&D Expenditure as % of GDP[1] | % GERD by Industry[2] | Industry GERD as % GDP[2] | Science &Technology Articles per 100,000 Population[3] | Patent Apps by Residents per 100,000 Population[3] | High Tech Exports as % Manufactured Exports[1] | High Tech Exports as % Total Exports[4] | High Tech Exports as % GDP[4] |
|---|---|---|---|---|---|---|---|---|
| Netherlands | 2.03 | 51.13 | 1.01 | 92 | 14 | 10.25 | 9.47 | 7.77 |
| New Zealand | 1.27 | 39.78 | 0.47 | 78 | 36 | 19.12 | 1.40 | 0.41 |
| Norway | 1.65 | 43.14 | 0.71 | 94 | 22 | 7.71 | 2.20 | 0.90 |
| Poland | 0.76 | 37.33 | 0.32 | 20 | 11 | 4.26 | 4.28 | 1.93 |
| Portugal | 1.52 | 46.04 | 0.63 | 44 | 6 | 10.01 | 2.14 | 0.80 |
| Russia | 1.09 | 28.16 | 0.32 | 10 | 20 | 46.99 | 1.19 | 0.35 |
| Singapore | 2.23 | 53.37 | 1.07 | 84 | 21 | 7.67 | 22.91 | 44.70 |
| Spain | 1.36 | 46.30 | 0.57 | 49 | 6 | 14.00 | 3.26 | 0.99 |
| Sweden | 3.39 | 60.95 | 2.01 | 99 | 24 | 26.55 | 6.57 | 3.05 |
| Switzerland | 2.87 | 60.78 | 1.80 | 124 | 19 | 7.65 | 11.22 | 7.52 |
| United Kingdom | 1.78 | 46.55 | 0.76 | 72 | 23 | 17.76 | 8.57 | 2.59 |
| United States | 2.76 | 60.85 | 1.66 | 65 | 90 | | 6.78 | 0.92 |

**Table 2: Selected R&D, Patenting and Export Statistics (Data Sources: 1. World Bank Open Data - 2011; 2. OECD.Stat - 2013; 3.calculated from World Bank Open Data and United Nations population data - 2012 & 2013; 4. Helgi Analystics - 2012**

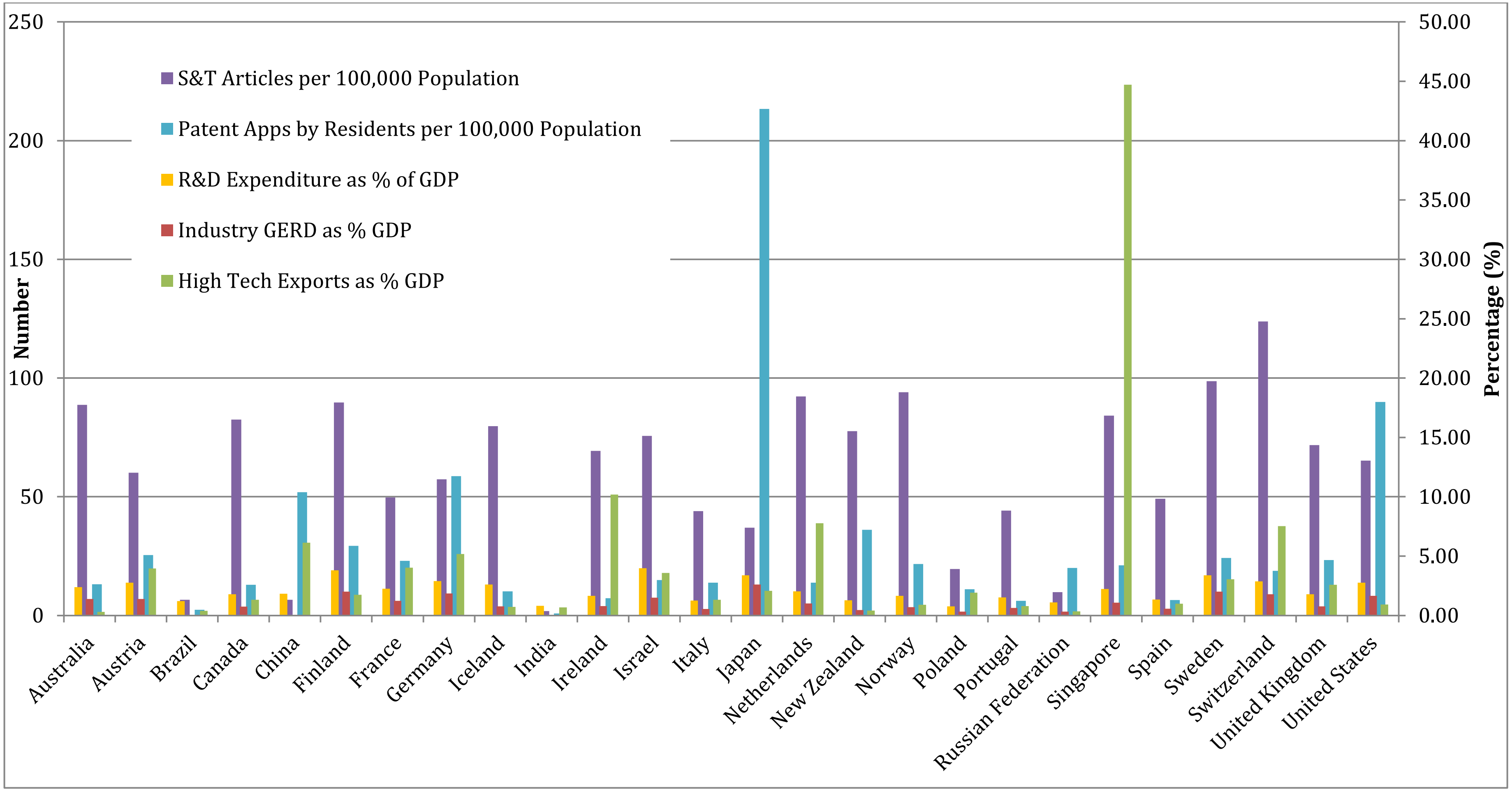


**Figure 2: Selected R&D, Patenting and Export Statistics (Data Sources: 1. World Bank Open Data - 2011; 2. OECD.Stat - 2013; 3. calculated from World Bank Open Data and United Nations population data - 2012 & 2013; 4. Helgi Analystics – 2012)**

This data suggests the links between investment in research and development, innovation and economic outcomes are not simple. Piketty (2014) asserts productivity growth is primarily dependent on knowledge and skill diffusion, with the recent economic advances of countries such as China occurring as a result of developing skill levels and adopting production modes comparable to those found in developed economies. International comparisons do not provide indications as to the nature of the policies, programs or investments governments should pursue to promote this diffusion or other drivers of innovation and the economy. In some economies, government investment may drive high tech exports, while in others it is driven by industry investment. High levels of innovation as indicated by patenting activity are not necessarily required for economies dominated by high tech manufacturing. The outsourcing of research and development, including across national boundaries, is increasingly common and will also play a role in the interactions between research publications, patenting and exports. High levels of government investment in R&D may be directed towards agriculture or medicine, which will not necessarily result in high tech exports. Innovation resulting from investment may be predominantly applied in the domestic context. Services exports may draw heavily on R&D. Manufacturing overall may play a relatively small role in the export economy due to an abundance of mineral resources. The global nature of technology companies may mean the manufacturing base relies on building parts and components that are then exported elsewhere before assembly and re-export. Indeed, the rise of multi-national corporations may have hampered the ability of national governments to realise effective results from policy implementation. As Tassey (2010) notes

> *"Essentially, the high-income economy must be the high-tech economy. However, larger manufacturing companies have responded to the competitive pressures of globalization and the lack of adequate domestic policy response* [in the USA] *by offshoring R&D as well as processing activities. This strategy has helped these firms but has also taken value out of the US economy."*

When making decisions as to where the policy gaps are, governments tend to compare various indicators and then develop policies in response to those indicators where they are perceived to be underperforming. For example, the level of industry-university collaboration in Australia is well below the OECD average (OECD, 2014). Therefore, the Australian government has determined that this is an area requiring policy attention in the form of initiatives such as the *Research Connections Grant* program (Commonwealth of Australia, 2014a). Similarly, the Scottish Science Advisory Council has identified that country's low levels of business R&D as an issue that needs to be addressed (2009). What is difficult to predict is what effect, if any, this will have on economic performance. Based on European Union countries, Sandu and Ciocanel (2014) suggest that increasing expenditure on R&D results in increased high-tech export activity. It should be noted they found the effects were greater for increases in business expenditure than for public expenditure, with the effects of increased business expenditure also being seen earlier than public expenditure. This aligns with earlier studies of OECD countries that deemed public funding of research has no effect on productivity growth (Park, 1995).

As noted by Geuna and Rossi (2015), there have also been a number of studies that support the contribution of publicly funded or academic research to increases in productivity, growth and GDP. For example, Haskel and Wallace (2013) report that research funded by the United Kingdom's various research councils increased total factor productivity, while the effect of privately funded R&D was insignificant. In the USA, Mansfield (1991) found that for seven industry sectors, between 9% and 11% of new products and processes were dependent on recent academic research. Further to this an average of 8% of products and 6% of processes were developed with 'very substantial aid' from academic research undertaken within the previous fifteen years (Mansfield, 1991). In 2016, Arora, Cohen and Walsh reported that for US manufacturers introducing new products, 5% were sourced from universities, with the pharmaceutical industry most reliant at 20%. While on the face of it 5% of new products coming from university research is low, this accords with Cohen, Nelson and Walsh's (2002) earlier finding that 8% of manufacturing R&D

projects utilised university prototypes and with Mansfield's (1991) findings above. However, as noted by Arora et al (2016), Cohen et al (2002) also report that 29% of manufacturing R&D projects made use of university research results, suggesting tangible university inventions are used by industry at around one fifth of the rate at which they make use of broader university research. Clearly there is a role for publicly funded research in supporting industry innovation. The challenge is in how to optimise the outcomes for both sides.

Recent work from the United States suggests research and development investment (from all sources) provides returns of between 83% and 213% to the state in which they occur, with significant spillovers also providing returns to other states (Blanco, Gu & Prieger, 2016). The wide range of returns determined by Blanco et al (2016) is indicative of the difficulties in tracing R&D investment through outcomes to economic activity. In Sweden, municipalities that are home to academic research institutions experience higher levels of economic growth thanks to spillovers, as do their neighbouring municipalities, (Lundberg, 2015). In addition, there are suggestions that industries which have high levels of R&D and innovation, tend to have more stable rates of growth and are less susceptible to the negative effects of general economic downturns (for example, Tang, 2015; Geroski & Machin, 1993).

Varying findings in regards to the effect of public research investment on productivity and economic gains may, like any attempt to assess research impact, partly be a function of time. Prettner and Werner's (2016) examination of OECD countries found that, while in the long term increased government spending on basic research leads to growth in per capita GDP, this is preceded by a period of slowdown in economic growth shortly after the increase in spending begins. They suggest this may due to the diversion of funds from other activities and/or the imposition of increased taxes to raise funds and speculate this short-term cost may explain why governments are often reluctant to increase expenditure on basic research (Prettner & Werner, 2016). For politicians focused on the election cycle and looking to maximise their re-election chances, short-term costs for long-term gains may not be worth the risk.

Obviously, R&D investment and its source is only part of the story when it comes to achieving improved economic outcomes. In their study of Canadian biotech companies, Hall and Bagchi-Sen (2002) found that while R&D investment results in increases in patent-related innovation, any association between this patent-related innovation and company performance is very small: company performance is more dependent on external factors such as access to capital and markets. At the time of their study, the biotech industry was relatively immature and this inability for patent–related innovation to influence performance could be considered a function of the stage in the company life-cycle. Interviews with biotech company managers suggested their performance is dependent on a combination of science-push and market-pull: ideas and innovations arise from scientific breakthroughs, but the selection of those which will be further developed into products and services is dependent on the availability of an accessible market (Hall & Bagchi-Sen, 2002). In line with this reliance on scientific breakthroughs to generate innovation initially, surveyed companies indicated that collaboration with universities, research centres and industrial companies was considered to be more important than collaborations with other biotech companies (Hall & Bagchi-San, 2002).

Governments around the world, particularly at the state, regional and local levels, have made significant investments in science and technology parks to encourage collaboration and innovative cluster development – *build it and they will come*. The development of successful clusters in the US, such as those associated with Stanford University and Massachusetts Institute of Technology, has been seen as a model to aspire to, with the ultimate prize being a local version of Silicon Valley.

While many governments appear to have accepted the link between science and technology parks and improved economic performance arising from increased innovation, in reality this link appears to be ambiguous. Seigel, Westhead and Wright (2003) found that for UK firms any effects resulting from being part of a science park were negligible. In China, Motohashi (2013) reports that while young, high-tech firms located in a Beijing park benefit from informal access to and relationships with the nearby university, there is little interaction between tenants themselves. Yang, Motohashi and Chen (2009) found that Taiwan residents of science parks do have higher levels of R&D productivity compared to their counterparts outside the parks. In Spain, Vásquez-Urragio, Barge-Gil and Modrego Rico (2016) report that small companies and those that actively pursue innovation gain greater benefits from being located in a science or technology park than larger or non-innovative companies. There have been a number of studies supporting the idea that where industry research is occurring in close geographic proximity to university or public agency research it tends to be more productive (for a summary see Geuna & Rossi, 2015), so either the geographical location of the park itself or the nature of its tenants would appear to be important.

The lack of a clear consensus on the overall benefit to companies of location in science and technology parks reflects the multitude of factors that affect innovation and productivity. Yang et al's (2009) Taiwan study suggests the ways in which some government policies apply to on-park firms may provide them with an advantage. Meanwhile, Motohashi's (2013) Beijing study identified administrative services provided by park management (such as human resources management) as being highly valued by the tenants.

Elsewhere it has been suggested technological proximity (as indicated by factors such as patent class) may actually be more important than geographical proximity when determining spillover levels (Aldieri & Cincera, 2009). Ben Letaifa and Rabeau's (2013) study of a Canadian ICT cluster reports that geographical proximity is no guarantee of the relationships built on trust and collaboration that encourage innovation, particularly when there are high levels of inter-company rivalry. In the United Kingdom, companies located in parks may be more likely to enter in to collaborative partnerships with geographically distant universities rather than the local one associated with their park (Minguillo, Tijssen & Thelwall, 2015). One can speculate that, even if the local university does not have the relevant expertise, having a relationship with a university via the park may make companies more comfortable with engaging with any university.

Follow-up work by Aldieri (2013) may support the idea of factors outside the park's mere existence being more determinant of improved performance. Aldieri (2013) reports that Europe and Japan have lower levels of cross-technology class spillover than the USA and suggests

> *"This result might be due to the relative distance of European, Japanese and American firms from the technological frontier. … American firms are able to benefit both from national and foreign spillovers and then assume the role of 'leaders' of the innovation market. However, Japanese and European firms benefit from national spillovers but they suffer from the competitive pressure at the international level and then they assume the role of 'followers' in the innovation context."*

If we accept that clusters and technology parks do promote spillovers and increased productivity it does not necessarily follow that government intervention by establishing clusters is the best course to follow. Rather, the early identification and support of emerging clusters may be more effective, as naturally evolving clusters tend to be more innovative than those formed in response to specific policy initiatives. As suggested by Ben Letafia and Rabeau (2013), government initiatives artificially create clusters based on proximities such as geography or organisation or cognition, while spontaneous clusters where companies connect voluntarily have social proximity built in to the cluster from the beginning.

Science and technology parks are often the most publicly-visible component of a regional innovation policy portfolio that aims to support a transition from reliance on declining traditional industries to higher value technology industries. But like the technology park itself, regional innovation policies are also constrained by external factors. Coenen, Moodysson and Martin (2015) suggest that the main challenges faced by regions are associated with the resources required for transformation (especially if there is a need to access capital from outside), and any limits on the ability of the region to influence decisions made at the national and international level that will affect market accessibility. The presence of dedicated, prioritising ICT innovation policies in regions of western Europe did not result in improved ICT performance for the period 2008 – 2012 (Kleibrink, Niehaves, Palop, Sorvik & Thapa, 2015), but the authors do caution that

> *"… the lack of a discernible link between the development of a dedicated ICT strategy and high ICT performance is baffling. In line with the broader strategic management literature, the link between rational strategic management and policy outcomes seems to be less robust than partly put forward by management science and policy initiatives.*
>
> *Yet, we must be cautious not to over-interpret these initial findings".*
> (Kleibrink et al, 2015).

The mere existence of a regional strategy does not tell us anything about its implementation, nor about how it interacts with other policies and strategies.

If innovation is the predominant driver in maintaining productivity growth for mature economies, then the USA's Silicon Valley is considered the holy grail of cluster-type environments, with governments at all levels manipulating policy levers in pursuit of a local version. This is despite the fact that not every region is capable of developing into a Silicon Valley style cluster, nor is it necessarily in their best interests to do so (Ooms, Werker, Caniëls & van den Bosch, 2015).

The Silicon Valley model of innovation is thought to be based on six elements and the features particular to Silicon Valley under each one: entry barriers, networks, research entities, social norms, ecosystem and sources of talents (Fung, Aminian & Tung, 2016). In comparing the characteristics of innovation activities in China and Taiwan with Silicon Valley, Fung et al (2015) found that while there were some differences in features, for each element there is usually at least one common characteristic amongst successful clusters. For governments, policy and regulation settings, along with funded programs can make a considerable difference to some elements: taxation arrangements influence investment, migration policies influence the diversity of the talent pool, decisions can be made about where and how to fund research institutes. Other elements are harder for governments to influence and are likely to require generational change: along with rewarding risk taking, tolerance and acceptance of failure are social norms consistent with the innovation activities located in Silicon Valley, China and Taiwan. (Fung et al, 2015).

With a population of 35.8 million (US Census Bureau) and GDP of USD$2,311.6 billion (US Department of Commerce, Bureau of Economic Analysis), California's internal market provides sufficient scale and diversity for companies to become reasonably established before expanding into the wider domestic and export markets. In the early stages of establishment, and for expansion, there is relatively easy access to capital. Capital access and financial constraints may be the limiting factor in reaping the productivity benefits of innovation and in converting investment in R&D to increased exports (Gorodnichenko & Schnitzer, 2013; Altomonte, Gamba, Mancusi & Vezzulli, 2016).

The varying ability of government to influence factors which appear to contribute to innovation clusters reinforces Ooms et al's (2015) assertion that while policy interventions can promote further regional development through the creation of favourable conditions, they cannot actually initiate nor sustain technological change and innovation within the region.

While there are undoubtedly common patterns to be found amongst successful innovation regions, intervention policies must be developed in the context of the region's characteristics, particularly research orientation and aggregation patterns (Ooms et al, 2015). As noted by Hill (2007), the concept of a national innovation system does not provide an instruction manual for creating the system. For each country attempting to improve its national innovation system, it has to find the mix of components which fits with its own governance principles, culture and place in the world.

Governments are sometimes tempted to select specific 'technology winners' for investment. At one level this is futile and it is always fraught with difficulty and involves significant risk. Even those in the vanguard of technological revolutions are said to have got it very wrong on occasion:

*"I think there is a world market for maybe five computers" – Thomas Watson, President, IBM, 1943*

*"I predict the internet will soon go spectacularly supernova and in 1996 catastrophically collapse" – Robert Metcalfe, Founder, 3Com, 1995*

(as quoted in Sparkes, 2014).

Mazzucato (2013) argues that while trying to pick winners is a high risk endeavour, it is possible for governments to do so and is also necessary for truly entrepreneurial societies. The US Government has actively supported the development of new technology sectors such as biotechnology and the internet and its applications from the earliest stages, successfully identifying them as investment areas.

In the defence context,

> *"The value of technology forecasting lies not in its ability to accurately predict the future but rather in its potential to minimise surprises."*
> (National Research Council, 2010).

Identifying emerging technologies is relatively simple – by definition they are beginning to make themselves known. What is far more difficult is determining which have the potential to become disruptive technologies, causing radical changes in the ways in which we live our lives and go about our business.

Governments need to think carefully about how they expect emerging or disruptive technologies to contribute to the economy. Arising from post industrial revolution manufacturing-based models of the economy, governments at all levels often invest in job creation, offering tax incentives or co-investment for large companies to set up operations in preferred locales. Any large company deciding where in the world it will establish a new R&D operation will have a multitude of inducements to consider in addition to their own requirements. But disruptive technologies may not result in significant job creation. Berger and Frey (2015) report that in 2010 less than 1% of US employees worked in industries that did not exist in 2000. Publicity surrounding this finding focused on wealth creation rather than job creation being the impact of technology industries, with Frey quoted as saying that as economies become increasingly digitised there may continue to be a stagnation of employment opportunities as the amount of capital investment required for digital industries is limited compared to for example, manufacturing industries (Oxford Martin School, 2015). However, this does not necessarily mean technological changes are not creating new jobs, merely new industries and types of jobs may not be created in the way that many of us might have thought they would be.

The fact that workers are not being employed in new industries as reported by Berger and Frey (2015) does not mean there are not new types of jobs being created within traditional industries and sectors. Nor does it mean the wealth being created necessarily has to be concentrated in a small section of the community. Based on the idea of the 'sharing economy', companies such as Uber, Airbnb and TaskRabbit are considered highly disruptive to traditional business models, causing considerable concern for established providers of services. However, these companies directly employ relatively few people and it can be difficult for service providers to earn the equivalent of a wage (Gobble, 2015). While not creating traditional jobs as such, these companies are creating wealth and it could be argued they are attempting to create wealth across a wider section of the community by providing access to alternative and supplemental income streams for individuals. Online-based technologies in particular are proving to be disruptive because of their ability to provide platforms which allow new players to enter traditional markets in numbers. Disruptive technologies do not have to drive change through the introduction of new industries or new ways of doing old tasks. It may be their potential for disruption is greatest when then they result in new models for how the economy arranges itself. In the western world, the twentieth century saw large, often multi-national corporations come to dominate economies in place of local, often family-run businesses. The internet is decreasing the distance between producers and consumers, both geographically and in terms of distribution. Large, imposing buildings are no longer necessary to entice customers in the door. Web portals remove much of the competitive advantage that large, established players have traditionally had. It is easier now for niche providers to access a global market. We may be in the early stages of major changes to how economies arrange themselves and it will take time for governments to adjust.

Given all of this, it does still make sense for governments to set broader priorities for research based on the social, environmental, and economical needs of their society. Chen, Chu and Yang's 2015 study of eleven OECD countries found that productivity growth tends to be promoted when R&D resources are concentrated within a small number of manufacturing industries. However, it is worth sounding a note of caution here. From Fung et al's (2015) comparison of innovation activity in Taiwan, it appears that successful specialisation in one area has the potential to stifle the ability to change direction when required - a reminder that one should not put all of one's eggs in the same basket.

## 3.3: Capacity Building & Capability Development

Whether we are discussing innovation at the organisational or national level, the ability to create, transfer, integrate and utilise new knowledge is dependent on many factors. Together, these factors form the absorptive capacity of a society or organisation and it is in the economic interests of governments to support the development of this capacity.

The economic concept of absorptive capacity as it applies to nations has been with us since the 1950s (Berger, 1982). In 1990, Cohen and Levinthal applied the term to a company's ability to recognise the value of new information generated outside the company, to assimilate it and to then apply it to activities critical to the company's innovative capacity and commercial activities. They suggest it is largely dependent on the amount of related knowledge that is possessed by the company (Cohen & Levinthal, 1990). Any knowledge or expertise held by an organisation is found within the individuals working there and embedded within the structures and systems that support those individuals. Over time, refinements have been proposed for Cohen and Levinthal's (1990) model of absorptive capacity (for example, Zahra & George, 2002; Nieto & Quevedo, 2005; Todorova & Durisin, 2007, Marabelli & Newell, 2014). Regardless of the details of the model, there are common underlying principles, including that companies can improve their ability to identify, assimilate and exploit knowledge that is developed outside by investing in a range of research or capability building activities (Fabrizio, 2009).

It is generally accepted that higher levels of workforce education correlate with increased innovation and productivity leading to stronger economies, due in a large part to greater absorptive capacity. It has also long been acknowledged that the more technologically progressive an economic entity is, the greater the value investment in education brings to the economy (Nelson & Phelps, 1966). Berger and Fisher (2013) suggest that in the US context,

> "*Providing expanded access to high quality education will not only expand economic opportunity for residents, but also likely to do more to strengthen the overall state economy than anything else a state government can do".*

Examining US cities, Berger and Frey (2015) found a correlation between average education levels and new industry creation. Furthermore, their analysis suggests cities which experience more rapid industrial renewal are those that have historically attracted skilled workers, on the basis that skilled workers are better able to adapt to technological changes affecting their industry or requiring them to move in to new industries (Berger & Frey, 2015). Following the large-scale introduction of computers to the workplace in the 1980s, many of the new jobs created in the USA have required abstract and conceptual skills, allowing those cities with initially higher skill levels to further exploit those opportunities (Berger & Frey, 2016). Similarly, West Germany saw a shift from manual and routine cognitive tasks to analytical and interactive tasks, which is thought to account for around half of the accompanying increase in required educational levels observed over the same period (Spitz, 2004).

Modern societies are heavily reliant on ICT and related technologies, thus we would expect that STEM skills are highly desired in the workforce. In addition, effective scientific training develops critical thinking and problem solving skills applicable across all areas of employment. Surveys of Australian employers support this desire for STEM skills, regardless of the sector in which they operate (Deloitte Access Economics, 2014). Seventy-five percent of Australian industry classes employ people with physical or mathematical science qualifications, while 69% employ people with biological science qualifications (Centre for International Economics, 2015; 2016). In addition, relatively small proportions of those with scientific qualifications work in the main science-based industries (Centre for International Economics, 2015; 2016).

Formal education in developed economies is structured on the basis that those doing the teaching have been educated and trained to at least one level, and often two, above that which they are teaching to. Teaching at primary and secondary levels is generally undertaken by those with tertiary level qualifications. For those teaching at secondary level there may be an emphasis on developing discipline knowledge as part of their training. Discipline teaching at the tertiary level is generally provided by those with postgraduate qualifications, most commonly a doctorate. At the simplest level, publicly funded research supports the training of new generations of higher education teachers who in turn train secondary and primary educators in addition to the graduate workforce.

In some ways, modern doctoral training remains close to its mediaeval roots, operating as an apprenticeship system where the candidate works under the supervision and mentorship of an experienced academic until considered sufficiently proficient. However the modern doctorate is predominantly a research apprenticeship, rather than a teaching apprenticeship as was originally practiced. Good researchers do not always make good teachers, and vice versa, so why is the doctorate increasingly the standard for university teaching? This may be due to the pre-eminent position of research universities in the international higher education sector, derived, in part, from general consensus regarding Humboldt's research-teaching nexus. A cursory examination of various university rankings shows the dominance of research-intensive universities (although given the reliance of most university ranking systems on research metrics, there is an inbuilt reinforcing bias). This prestige allows these institutions to be highly influential and provide examples of hiring practices that others can aspire to.

Globally, participation in higher education has increased dramatically in recent decades. The years 2000 to 2007 saw an estimated increase of more than 50% in the number of tertiary education students, placing considerable pressure on the limited pool of suitably qualified academics available for teaching (Altbach, Reisberg & Rumbley, 2009). While it is not possible to determine exact qualification levels across the international higher education system, Altbach et al (2009) suggest the number of teachers in China's rapidly expanding university system that hold doctoral qualifications may be as low as 9%. This contrasts with around 70% of academic staff across the Australian higher education sector holding doctoral qualifications (Department of Education and Training, 2016). In the United Kingdom it is thought less than half of the academic workforce hold doctorates, with doctoral qualified staff making up more than 80% of the academic workforce in only twelve of the UK's more than 100 universities (Malcolm Tight, as quoted in Grove, 2012). South Africa's universities of technology aspire to double the proportion of academic staff with doctoral qualifications to 40% over the next three years (Moyo & Williamson, 2016). Clearly there is a growing international demand for doctoral qualified individuals, many of whom are trained via public investment in research.

Outside the need for suitably qualified teachers within higher education, research and higher degree training provides valuable capability for other sectors.

Martinez-Senra, Quintas, Sartal and Vasquez (2015) undertook a study of the basic research activity undertaken by more than 8,000 Spanish firms in the years prior to the 2008 financial crisis. They conclude that undertaking basic research improves product innovation in the short term and postulate that companies which focus exclusively on market-based based R&D end up neglecting the development of the human capital of their own technical staff. This then results in a gradual loss of the firm's capacity to support substantial product innovations over time. This aligns with Cohen and Levinthal's (1990) model in which investment by an organisation in R&D contributes to the development of absorptive capacity, even when the results of the R&D are largely released into the public domain, and also with the findings of Su, Ahlstrom, Li and Cheng (2013), that for Chinese firms,

> *"… in addition to their individually positive effects, knowledge creation capability and absorptive capacity have a synergistic effect on product innovativeness."*

Furthermore, Su et al (2013) suggest that in times of great technological change, the contribution of knowledge creation capability to innovation activity increases.

Regardless of the benefit, supporting in-house research programs requires significant commitment and resources, beyond the capability of many companies. Therefore they need to maintain their human capital through the regular importation of new skills, and to access the results of research produced by others. Training in high-level skills and the production of research results is often highly dependent on public investment through the tertiary education system.

Increased absorptive capacity for innovation is just one of many reasons for nations to aspire to an educated society. For our purposes, this increased absorptive capacity in relation to high-tech innovation is largely dependent on STEM education levels within the community. But this is far from being the only skill factor.

In addition to increasing STEM participation and skills, there is also a need to develop business management skills to enable successful exploitation of technological innovations. According to the Australian Government

> *"Making innovation work requires a workforce with sophisticated skills of all kinds – including leadership and management skills."* (Department of Innovation, Industry, Science and Research, 2009).

Meanwhile, in the same year, the Scottish Science Advisory Council noted that

> *"Developing the knowledge and insights to be able to make well-informed (derisked) investment decisions on R&D and innovation is difficult to acquire, either through formal business training or experience."* (Scottish Science Advisory Council, 2009).

Work undertaken by Bloom, Genakas, Sadun and Van Reenen (2012) as part of the World Management Survey found that management practices score highest in the United States, Germany, Sweden and Japan, countries that were ranked third, fifth, tenth and sixth respectively in the 2014-2015 Global Competitiveness Index (Schwab, Sala-i-Martin, Barth Eide & Blanke, 2014). The World Management Survey found there are strong correlations between a number of financial performance indicators and management performance scores, both at the company and national level. In addition, improvements in management practice can result in greater increases in company output than comparative increases in investment in either labour or capital (Bloom, Dorgan, Dowdy & Van Reenen, 2007). Analysis of Australian data collected as part of the World Management Survey found that for manufacturing firms there is a positive correlation between management performance and company performance, and that

> *"In all, variation in management performance is attributed to education level of employees and managers, firm size, ownership by a multinational firm, diffused ownership structure, plant manager hiring and investment autonomy and the level of vertical integration.*
>
> *In concluding, our results suggest that the development of management skills is crucial to the improvement of Australia's manufacturing sector productivity performance."* (Agarwal, Brown, Green, Randhawa & Tan, 2014).

Absorptive capacity is affected by more than just the educational attainment of the available workforce. Studies of three of South Korea's major IT clusters found that absorptive capacity and innovation performance are largely determined by the company's support technologies, staff expertise and management advocacy, with absorptive capacity mediating the relationship between these three factors and actual innovation performance (Kwon Bae, 2015). Similarly, European studies have found that support from the top levels of management for technology and technical skills, along with effective organisational learning processes, contributes to increased entrepreneurship and performance (Martin-Rojas, Garcia-Morales & Bolivar-Ramos, 2013).

Roberts' (2013) study of computer manufacturing and software publishing companies in the USA found that levels of data integration and connectedness influence absorptive capacity. In this instance, the ability to easily access and share the company's knowledge base (for example, knowledge about customers, emerging technologies and markets) when combined with high levels of informal and formal contact across internal divisions, improves the ability of employees to identify, integrate and utilise external knowledge in order to identify and exploit innovative and commercial opportunities (Roberts, 2013). Meanwhile in Germany, Duchek (2015) reports that company divisional structure, centralised versus decentralised R&D functions, the presence or absence and nature of 'gatekeeper' positions and the presence or absence and nature of 'interface' positions all influence the absorptive capacity.

All the above examples have in common that at their core they are management decisions – decisions as to how to organise and operate activities. This then returns us to the idea that for innovation, including technological innovation, it is not only the STEM capabilities that count. Indeed, managerial capabilities may be more important. A study in Canada of subsidiaries of a multi-national corporation that had significant ICT transfers imposed by the foreign parent found that absorptive capacity was insignificant in the success of ICT transfer and adoption, but that procedural justice was a predictor of success (Verbeke, Bachor & Nguyen, 2013). That is, the way in which upper management introduces these changes is more important for success than the ability of staff to absorb them, a situation familiar to anyone who has been involved in major organisational changes, whether procedural or structural.

While management skills are obviously important, one should be careful not to promote unreal expectations regarding the ability of a single managerial 'genius' to turn around a company's innovation performance in the manner of Steve Jobs return to Apple. Cho, Halford, Hsu and Ng (2016) suggest that while the latent characteristics of individual managers do play a role in company innovation, the influence of the characteristics of the company itself (such as corporate culture, product nature and competiveness) is actually larger. Corporate culture is a manifestation of more than just its management and also plays a part in determining what managerial characteristics are recruited to the company. As such, separating the influence of manager and company characteristics will be very difficult.

Regardless of the full extent to which management influences innovation, it would appear that policy attempts to increase STEM skills will be of limited value unless they are accompanied by attempts to also increase managerial skills. Yet this also may not be enough. While technical skills supported by appropriate management may be vital, innovative organisations also value expertise and skills associated with creativity, marketing, cultural understanding, communication, problem solving and leadership. Innovation leaders are often 'specialised generalists' having deep knowledge in one particular area supported by a broad understanding across many others, with the variety of skills possessed by the organisation as a whole reflecting the mix of skills held by its staff as individuals (Cunningham, Theilacker, Gahan, Callan & Rainnie, 2016).

Care does need to be exercised when focusing exclusively on STEM education as a means of supporting regional economic development. In finding that specialised high-tech and knowledge intensive human capital can have a negative effect on economic growth, Teixeira and Queirós (2016) suggest that if countries do not have industry and sectorial structures which are able to ensure highly skilled and educated workers are fully integrated then the resultant skill mismatch (usually via over-education) brings attendant decreases in job satisfaction and personal productivity which then impact GDP growth. That is, for highly developed economies, as knowledge intensive industries grow as a share of the economy, development of human capital also becomes more important, but for economies in transition, investing in education alone will not help economic growth. Education policies must therefore be considered as part of an integrated development agenda including other relevant policy areas such as industry, regulation, finance and research.

If, as has also been suggested, we are moving towards a post-scientific society, then

> *"…, the creation of wealth and jobs based on innovation and new ideas will tend to draw less on the natural sciences and engineering and more on the organizational and social sciences, on the arts, on new business processes, and on meeting consumer needs based on niche production of specialized products and services in which interesting design and appeal to individual tastes matter more than low cost or radical new technologies."* (Hill, 2007).

Elements of this can be seen in the emergence within many western societies of movements concerned with bespoke, handcrafted, small-scale and local design and production. This appears to be based on a form of exclusivity that is different from that traditionally associated with price and associated more with the hunt (although platforms such as *Etsy* make the search easy for all). The extent to which we may be moving towards a post-scientific society in developed economies is unclear, but we are seeing significant challenges posed to established modes of conducting business. Disruptions to the ways in which our economies operate will add further complexities to our attempts to recognise and assess research impact.

## 3.4: Tackling the Grand Challenges

In 2015 the United Nations set seventeen Sustainable Development Goals across areas including health, poverty, infrastructure, sanitation and education. Targets under each goal are indicative of the complex, multi-faceted challenges facing both individual societies and the world as a whole. Meeting these challenges will require highly collaborative, multi-disciplinary approaches. For example, the Health and Well-being Goal includes the target of ending the epidemics of AIDS, tuberculosis, malaria and neglected tropical diseases by 2030 while also combatting hepatitis, water-borne diseases and other communicable diseases (United Nations, 2015a). Clearly this requires action and advances in public health policy, diagnostics, epidemiology, treatment and sanitation amongst others.

Predominantly occurring in regions of entrenched poverty, there are a number of factors which can contribute to a disease being termed 'neglected'. One is a reluctance by pharmaceutical companies to develop and manufacture preventative or treating medicines due to a perceived lack of a market – from a profit perspective there is little value in spending money to develop a product which those who need it cannot afford to buy. In this instance governments are required to support any underlying research required or subsidise the work by guaranteeing a viable market.

Solving large, complex problems is often beyond the capabilities of any single organisation. The risks may be unpalatable. Without a profit motive, there is little incentive for industry to be involved. In these instances it can be helpful to have a 'neutral' sponsor of the work and the scale required means this role will generally fall to government.

These grand challenges are sometimes referred to as 'wicked' problems and

> "… *require a multi-disciplinary approach in finding possible solutions, which engages different knowledge bases and combines both the 'hard' sciences and social sciences and the humanities. The global nature of grand challenges and their wide-ranging implications are also characteristic."* (Amanatidou, Cunningham, Gök & Garefi, 2014).

They are often reliant on novel technologies and applications, with new ICT platforms driving many approaches. Amanatidou et al (2014) note the nature of these challenges means that solutions will require governance and policy co-ordination across varying levels, geographical regions and policy domains.

These factors will present their own challenges in regards to assessment and evaluation.

## 3.5: National Security

*“Without education, we are weaker economically. Without economic power, we are weaker in terms of national security. No great military power has ever remained so without great economic power”*

- Jon Meacham, Pulitzer Prize winning author, former Editor-in-Chief, Newsweek, American Voices: Jon Meacham on Saving Our Schools, and Everything Else We Value, 2012

The term national security refers to the protection of a country’s interests and is generally thought to cover both defence and foreign relations activities. In addition to military security, it encompasses a wide range of policies and actions undertaken within the state such as economic, infrastructure, energy, resources, health, and politics. At its most basic, national security aims to ensure a country is in a position where it is capable of successfully preventing or resisting hostile or destructive actions taken against it by other nations, groups or individuals. Prevention is generally achieved by maintaining a military advantage over other nations (real or perceived); or through friendly foreign relations. Resistance, meanwhile, requires a combination of military prowess, prescient intelligence, secure infrastructure and resilient institutions.

We live in an interconnected global economy and developed countries, in particular, are reliant on infrastructure and institutions that are underpinned by sophisticated ICT systems for day-to-day functioning. Military superiority is no longer the guarantee of security that it once was, with networked and interconnected systems vulnerable to both state-sponsored and lone wolf attacks. Infrastructure such as banking systems, traffic control, electricity grids and communications networks can all be targeted to paralyse modern cities and cause significant damage. An individual with a laptop can now hold societies hostage more effectively than armies could besiege a city in the past.

Development, maintenance and defence of ICT-reliant infrastructures requires a critical mass of highly qualified individuals willing to use their skills in support of the state. Countries which are unable or unwilling to train their own citizens are reliant on importing these required skills from other nations. This is potentially an expensive and high-risk solution: in addition to having to compete in the global marketplace for in-demand skills, the chances of recruiting those with divided loyalties or nefarious motives are greatly increased.

The need for knowledgeable experts occurs at the national as well as the organisational level. When purchasing technology, whether locally-sourced or imported, there is a pressing need to ensure it is fit for purpose and adequate value for money is being received. Any consumer knows the feeling of powerlessness when having to select the best version of a product which they know nothing about and many will have at least one experience of being sold something totally unsuitable by a clever-talking salesperson. This is a classic example of the adverse selection problem associated with the principal-agent model of acquisition that shall be discussed further in Chapter 10.1

Given the relatively high contribution of high tech exports to France's GDP, it may be significant that Bertrand and Mol's (2012) study of French companies found that absorptive capacity developed through internal R&D is positively associated with foreign outsourcing of research and that this foreign outsourcing is more effective for both product and process innovation than domestic outsourcing of R&D. Having an internal R&D program ensures that a company has the capability to both assess the quality of the outsourced work and properly utilise its results. It is able to overcome the adverse selection problem. This same logic applies at the nation level.

When implementing complex technologies developed elsewhere there is often a need for customisation to take in to account local conditions, whether they be environmental, regulatory, or cultural. New systems will have to interact with established technologies, legacy issues come to the fore. The rate at which technology is advancing means that systems are often superseded by the time they are implemented. It is never as simple as 'plug and play'. As noted by the Centre for International Economics (2015), when evaluating a country's scientific community, not only must the value of any locally created discoveries and solutions be considered, but there also needs to be consideration given to the question of whether it acts as an efficient and necessary mechanism for identifying and applying research discoveries and solutions in the local environment.

Within the Australian context, the publicly funded Defence Science and Technology group (formerly DSTO) plays a key role in national security:

> *"DSTO provides scientific and technical support to current Defence operations; investigates future technologies for Defence and national security applications; and, ensures Australia is a smart buyer and user of Defence equipment. DSTO also develops new Defence and national security capabilities; enhances existing capabilities by increasing performance and safety, and reducing the cost of ownership of Defence assets; works collaboratively with other science and Government agencies to strengthen national security; and assists industry to become better at supporting Defence's capability needs."* (Commonwealth of Australia, 2014)

Shahiduzzaman, Layton and Alam (2015) conclude that increasing investment in ICT capital led to improvements in both labour and multi-factor productivity growth in Australia over a long time period, suggesting an economic benefit. While the link between ICT investment and productivity growth may actually be ambiguous (Cardona, Kretschmer & Strobel, 2012; Hajli, Sims & Ibragimov, 2015) it would seem that as a nation with a relatively poor historical record in fully developing its own technologies, yet enthusiastic adoption of new technologies, being a "*smart buyer and user*" is crucial for Australia for a number of reasons.

Ferguson (2010) suggests there are three main reasons for investing in defence research and development:

1. to maintain the research and industry capability to provide for essential needs which cannot be sourced from elsewhere;
2. to maintain independence and lessen reliance on those answerable to other governments; and
3. to maintain international credibility and enable contributions to vital alliances.

Ferguson (2010) goes on to quote a senior defence scientist who encapsulates the opportunity costs associated with an inadequate defence research sector:

> *"[W]e end up beholden to the market with no control over the price we pay for equipment and the capability we receive. Local production (based on local R&D) leaves us options and some leverage in the market place. The advice that DSTO provides Defence in policy/buyer/user areas is backed by its R&D, so defence R&D is an essential component of defence capability. The long-term consequences of bad decisions can be unexpected and persistent, so good advice is essential."*

Given that rapidly advancing technology is essential to both the defence and operations of modern societies, these comments are just as applicable to ICT. Indeed, they are applicable to all areas of research. While recognising there is a very small likelihood of retaliation occurring in the event of a country 'free-riding' on pure research produced by other countries, Davies and Slivinksi (2015) assert that the undertaking of pure research results in individuals who have been trained such that they are able to engage with and understand this research. The resultant decrease in training arising from decreased pure research will, over time, lessen the ability to understand and exploit research undertaken elsewhere so that eventually there will be no benefits to free-riding (Davies & Slivinski, 2015). Similarly, in assessing the contribution of physical and mathematical sciences to the Australian economy, the Centre for International Economics (2015) notes that when translating foreign-sourced research into knowledge that is useful locally, there is a need to evaluate and select the appropriate work before beginning the translation. Therefore, we must understand what skills are required to undertake this crucial task, and determine what is the best way to ensure we possess those skills as a nation.

In addition to allowing Australia to be self-sufficient in food production if required, agriculture and horticulture are significant providers of export income. Again, this is an area where governments at both the Commonwealth and State levels invest in significant research via organisations such as the Rural Industries Research and Development Corporation (RIRDC), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the Grains Research and Development Corporation (GRDC).

In Australia, it would seem that the question as to whether there is a need for government investment in research outside the universities in support of defence (physical security) and agriculture (food and economic security) has been resolved, with a definitive yes. These publicly funded research agencies develop skills and capability, assess international developments, innovate in their sectors and provide insights as to future needs and directions. They allow Australia to be a *"smart buyer and user"* and develop exportable products. Given the reliance on ICT across all aspects of society it would seem that a mature ICT research environment is crucial to national security in the modern age.

## 3.6: What About Industry?

As a suite of highly diverse technologies, ICT is driving many of the disruptions that are occurring across industry. New products and new ways of engaging with customers are disrupting traditional business models at a rapid rate. 'Big data' and the 'internet of things' (IoT) are thought by many to be driving the fourth industrial revolution, following on from those driven by mechanisation, electrification and digitalisation (Drath & Horch, 2014). There are those who argue the long-term impact of the ICT revolution will pale beside that of the agricultural, printing and industrial revolutions. This is due to computing, in the main, having allowed us to do things faster, cheaper, better and easier, rather than allowing us to do totally new things (Gordon, 2000; Das, 2015). It is not possible to gauge the overall impact of such societal revolutions when in the midst of them, so only time will tell the true impact. But it is evident there are significant changes occurring in the way our economies organise themselves.

To survive and thrive, industry actors must innovate, both in the products and services they offer and in the ways in which they go about their business. The role of industry in ICT research may be dependent on what you are wishing to achieve.

Industry is particularly well-placed to undertake research aimed at developing new consumer products and services, delivering jobs and economic returns. Compared to publicly funded research entities they are closer to the customer with a far greater awareness of what the market desires and the constraints under which they must operate.

While industry research is primarily focused at the applied end of the spectrum, there have always been a small number of companies which also participate in basic research. In 1990, Rosenberg noted that basic research by industry is concentrated in a limited number of sectors, and within those sectors the research is undertaken by a very small number of companies, usually large ones. Sometimes, this basic research has emerged out of what was originally conceived as applied research. This may be a manifestation of Mokyr's (2011) observation regarding the industrial revolution: that scientific and technological advances result as much from transfers from practice to theory as from the more commonly recognised theory to practice. While noting the distinction between basic and applied research is quite arbitrary, Rosenberg (1990) nominates Bell Labs' contribution to the establishment of radio astronomy as an example of this phenomenon and also notes that

> *"Historically, some of the most fundamental scientific breakthroughs have come from people like Carnot, Pasteur and Jansky, who thought they were doing very applied research, and who would undoubtedly have said so if they had been asked at the time."*

Rosenberg (1990) also points out that within industry, the researchers themselves may consider themselves to be undertaking basic research while their managers consider them to be working on applied.

The current emphasis on applied research means industry research outputs tend towards patenting and trade secrets leading to products and services rather than publication in the academic literature. Emerging technology fields appear to be disrupting this traditional model, just as they are disrupting economic models, with significant numbers of SMEs contributing to larger than expected levels of industry authorship (Shapira, Youtie & Kay, 2011). It has been suggested the high costs associated with patenting may influence SMEs to use academic publishing in strategic ways to support a number of organisational goals (Li, Youtie & Shapira, 2015).

Like many business operations, R&D has become an item to be outsourced. It is thought that many large pharmaceutical companies are moving towards outsourcing 40% of their R&D spend, and expect that all clinical operations will be outsourced in the future (PwC, 2014). The benefits of outsourcing appear to be mixed, with other factors influencing the benefit received. From econometric analysis, Grimpe and Kaiser (2010) conclude there is an inverse u-shaped relationship between the degree of R&D outsourcing and innovation where increasing the amount of outsourcing increases innovation to a tipping point from which any additional R&D spending begins to have a negative effect.

Small firms appear to benefit from outsourcing basic research while medium and large firms benefit more from basic research that is undertaken in-house (Andries & Thorwath, 2014). These studies add further levels of refinement to Fabrizio's (2009) assertion that undertaking their own basic research accelerates the pace of innovation for firms and that they can further boost this by also having collaborations with academic researchers.

It is worth noting that changes in the level of government research funding can also affect industry investment in research. In the United Kingdom, increased government spending on research has been accompanied by increases in spending by private and charitable organisations (Reid, 2014). Reid (2014) thinks that as public funding decreases, so too does the attractiveness of the UK research base for industry and charity as a place to invest. It is estimated that for every additional pound investment by the UK government and charities in medical research, £0.83 - £1.07 extra spend is made by the private sector, much of it within twelve months (Sussex, Feng, Mestre-Ferrandiz, Pistollato, Hafner Burridge & Grant, 2016). In this instance, government investment is stimulating private investment. The reasons for this will be many, but a key factor is likely to be the resultant availability of a sufficiently sized pool of skilled labour from which to recruit and it is reasonable to expect similar a similar effect occurring in technology sectors.

As government funded research is the prime source of training for skilled workers who move in to industry, and provides access to expensive infrastructure, it should be obvious that government and industry research can not be totally de-coupled.

## 3.7: Filling the Gap

In economic terms, much scientific information can be viewed as an excludable public good: use by one entity does not prevent others from using it - hence a public good – but you can prevent others from accessing it – hence excludable (Davies & Slivinski, 2015). An example of this is the traditional academic publishing model, where only those who pay for journals are able to access the knowledge, but any one subscriber does not prevent any other subscriber from also being able to use the information. As Davies and Slivinski (2015) note, while the market can provide excludable public goods, they will be inefficient by virtue of not providing the optimum amount.

The notion that there is a market failure in regards to research, and hence the need for government intervention has been with us for a number of years. In 1966, Mansfield asserted that

*"… three elementary, but important points should be noted regarding the allocation of resources to the production of knowledge in a perfectly competitive economy."*

These points can be summarised as

- if profit is the motivation for producing knowledge, there will not be as much produced as is socially desirable (especially in regards to basic research);
- knowledge is generally free to disseminate once produced, thus the need to keep it secret in order to profit from it means that the benefit to society is inefficient; and
- some aspects of the competitive process associated with the market will still be desirable, particularly when dealing with large uncertainties.

Effectively, public funding of research is an attempt to address the gap identified in the first point, while the patenting system and the marketplace attempt to address the final two.

The prolonged debate concerning patenting of isolated gene sequences, and in particular the US Supreme Court action regarding the BRCA1 and BRCA2 genes, provides an example of the tension between the market's requirement for profit and the wider benefits to society. Mutations of the BRCA1 and BRCA2 genes are associated with some forms of breast and ovarian cancer. Patenting of the genes by the company which identified and subsequently cloned the sequences for use in testing was thought to have led to unnecessary restrictions on further research (Kesselheim, Cook-Deegan, Winickoff & Mello, 2013). (It is also worth noting that according to Kesselheim et al (2013) the research which led to the identification of the chromosome region where the sequence is located was publicly funded). While the decision to overturn the patent was based on the idea that a naturally occurring gene sequence can only be discovered, rather than invented (Kurts, 2013), many of the arguments presented as part of the case detailed the ways in which enforcement of the patent rights hindered the realisation of the benefits to society from knowing the sequence (Kesselheim et al, 2013).

Publicly funded research therefore encourages the research community to produce the optimal amount of knowledge for benefit to society and when government also mandates that the outputs are freely available it ensures that optimal benefit can potentially be gained.

From a government intervention perspective, the difficulties lie in determining the optimal amount of funding in the context of competing priorities; the mechanisms by which the funding should be distributed; to whom it should be distributed; and where in the research-development continuum it should be targeted. The market inefficiency rationale suggests that most effort should be directed towards the basic end of the continuum. However, if funding is to be determined purely by impact, then it would make more sense to direct funding towards applied research and development. Enabling technologies may provide the greatest opportunities for widespread impact, suggesting funders seeking impact should direct funds towards research that focuses on the development of ICT platforms.

# Chapter 4: Value for Money? – Having an Impact

*"What would not have happened if you did not exist, and how much would society have missed?"*

– William Banholzer, former Executive VP and CTO, Dow Chemical, Address to the President's Council of Advisors on Science and Technology, 2013

*"Research impact is the demonstrable contribution that research makes to the economy, society, culture, national security, public policy or services, health, the environment, or quality of life, beyond contributions to academia."* – Australian Research Council, Research Impact Principles and Framework, 2015

Research funders routinely receive requests for funds well in excess of the monies available for distribution. The *Heilmeier Catechism* is a commonly used framework to assist in determining what projects to support, both in public and private research. Formulated by former Defence Advanced Research Projects Agency (DARPA) Director George Heilmeier, the catechism is a series of questions for researchers and assessors to consider:

- What are you trying to do?
- How is it done today, and what are the limits of current practice?
- What is new in your approach and why do you think it will be successful?
- Who cares? If you succeed, what difference will it make?
- What are the risks?
- How much will it cost?
- How long will it take?

- What are the mid-term and final "exams" to check for success?"[3]

The questions of "who cares?" and "what difference will it make?" are essentially questions of research impact. But what is impact and how do we recognise the impact of research?

## 4.1: What is Impact?

At its most basic, impact means *"a marked effect or influence"* when used as a noun and "*have a strong effect"* when used as a verb (Oxford Dictionary of English, 2005). In the assessment context, the concept of *additionality* may also come in to play, where additionality is considered the extent to which something happens as a result of an intervention, where that something would not have happened in the absence of the intervention. Alternatively, the intervention may prevent an unwanted event happening or may alter the timeframe in which something occurs.

Logic tells us that before impact can be assessed it must first be observable, even if it is not easily measureable. It must be evident that something has changed and that the change, or at least some aspect of the change, can be directly attributable to the research preceding it.

Impact can be direct or indirect. It can be positive or negative. It can be minor or major. It can be short-lived or permanent. But it must always be an observable change.

Samuel and Derrick's (2015) interviews with health-related research evaluators for the UK's 2014 Research Excellence Framework found that while impact was predominantly viewed as being an outcome (a change or a difference), there were a range of views regarding how the outcome was to be characterised, how you could compare outcomes and where research ends and impact begins. Clearly, how impact is viewed and considered is a personal thing.

[3] http://www.darpa.mil/work-with-us/heilmeier-catechism, accessed 2nd November 2016

It is also worth noting that impactful research may not always be important research, especially when we are considering traditional academic impact measures and short time frames. Casdevall and Fang (2015) compare the importance but lack of citation impact (for decades) of Mendel's genetic discoveries with the high (positive) citation impact of a 2011 paper reporting a bacterium making use of arsenic in its DNA, which has since been found to be an error. Time has shown Mendel's work to be vitally important in laying the foundations for our continuing understanding of genetics. Arsenic as a component of DNA had the potential to be very important but time has shown the findings of this research to be a mere distraction.

When attempting to assess the impact of different activities a choice may need to be made between desired reach and intensity. This is likely to be a particular issue when evaluations are being used to inform rankings or funding decisions. Reach refers to how widespread the impact is, for example the numbers of people affected, while intensity refers to the strength or size of the effect. How does one compare a big impact on a small number of people with a smaller impact on large numbers? Is being able to double the life expectancy of those with an extremely rare disease a more meaningful impact than lessening the average time lost to work due to a common minor illness by 0.25 days?

Assessment is often built on a series of value judgements, many of which will be subconscious. This is just as true for impact as a whole, as it is for quality. By electing to examine impact in a well-defined area (for example on road deaths, on sales income) many of these value judgements can be put aside. However, if you are using impact to inform decision making, a narrow focus will limit the number of outcomes you can validly compare.

## 4.2: Context is Everything – Defining Your Place in the World

*“”Is everyone who lives in Ignorance like you?” asked Milo.*

*“Much worse,” he said longingly. “But I don’t live here. I’m from a place very far away called Context.”*

– Norton Juster, The Phantom Tollbooth, 1961

As will be discussed in Chapter 5.1, assessment implies making a value judgement about an activity and any judgement is heavily influenced by both the values of the observer and the environment in which the activity is being undertaken. The variety of contexts in which research is undertaken, along with the issue of reach versus intensity, raises questions about the validity of using metrics for assessment, particularly when impact assessments are used as a comparative tool or for decision-making purposes.

As noted by Simons (2015), context is more than a static description of time, location and circumstance, but also encompasses cultural norms and assumptions, interests, values, history, people and their roles. Rog (2012) argues that context should be the starting point when developing assessment programs, so that the most appropriate evaluation approaches can be used to gather evidence for any actions that may be required.

In many countries a significant portion of publicly funded research is undertaken within the university system – in 2008 more than 60% of government funded research expenditure in OECD countries was undertaken by the higher education sector (OECD, 2015). Within Australia, like many countries, the university sector itself is quite varied: long-established, research intensive universities located in major cities operate alongside smaller, younger regional universities where research is a relatively minor part of operations. The expectations local communities hold for these diverse institutions can be quite different. As such, one would expect the impacts which are sought and valued are also varied, along with the fields in which they occur. However, as noted by Uyarra (2010):

> *"Policy-makers and commentators seem to harbour very high expectations about the contributions of universities to regional innovation, despite the complex tensions and inherent diversity that characterize the sector. This complexity and diversity tends to be assumed away in a monotypic vision of universities, which portrays them as highly flexible, integrated and strategic actors".*

Both the sector and individual universities are subject to many and varied policy expectations – they are asked to be all things to all people. Universities themselves must therefore make decisions regarding the relative value of responding to competing policy directions within their local community.

The interplay between this variation within the higher education sector and research assessment can be observed in the UK Research Excellence Framework (REF). For the 2014 evaluation, 25 research intensive institutions accounted for half of the case studies submitted for assessment, dominating the impact reported in medical and related fields. Less research-intensive institutions were found to make a disproportionate contribution in areas such as sport, regional innovation, performing and visual arts (King's College London & Digital Science, 2015). Differences between expected and actual numbers of submissions for given topics by institutions is likely to be due to a combination of research specialisation and the choices made by each institution as to which case studies should be submitted for consideration. While specialisation may limit the choices, the fact is the institutions themselves must recognise these impacts as being valuable to their communities or else they would not undertake nor submit them.

In addition to their role in regional and cluster development, universities can play a significant role as cultural intermediaries, promoting the development of vibrant arts and cultural communities. Operating at the interface between creators and users, these institutions can provide training in necessary skills and a location where the acquisition and exchange of knowledge can take place

(Rantisi & Leslie, 2015). Universities can also play a role in encouraging community involvement in the arts by acting as venues, initiators and patrons for artistic and cultural events (Mooney, 2009; Bishop, Kavanagh & Palit, 2010; Wilson, 2016). Wilson (2016) asserts that in Australia, the university sector plays a core role in the visual and performing arts sectors, being home to a large amount of the country's artistic infrastructure and practitioners, yet this contribution is largely hidden from the government and the wider community. In addition to undertaking research in the arts, universities are often the custodians of significant cultural collections. Both of these activities will often result in non-traditional research outputs which can be a disadvantage under some assessment regimes.

Regional universities often play an important economic role as an employer and purchaser. Providing alternative opportunities for young people they play a key role in shaping regional demographics. The research they undertake may be highly localised, and while vital to their community, of no consequence in the wider world. Within Australia, each of the regional universities'

> *"… regional engagement 'story' simply couldn't exist anywhere else. While there are many common themes applicable across regional and rural Australia, … each institution and each campus, has a strong sense of place and unique identity that is inextricably linked to the historical, physical, demographic, social, cultural and environmental characteristics of its region"* (Regional Universities Network, 2013).

And, as noted by Gunasekara (2006), regional universities face particular challenges when attempting to engage with industry, with generally limited opportunities for local engagement and national priorities which may not align with local needs.

It is natural to expect that universities located within big cities, where they may be one of a number, operate in a vastly different context to that of their counterparts in small, regional cities. But given that assessment by its very nature implies a value judgement, the context is required for making informed judgements. For this reason, metrics-based assessments have the potential to unfairly advantage or disadvantage institutions by virtue of their size, location and the expectations their local communities have of them.

In addition to the context within which a piece of research is undertaken or a research organisation operates, we must also be mindful that assessments themselves are undertaken within varying contexts. Changes in the political, economic and social environment will all result in variations to the context in which regular assessments are done. This can mean that the outcomes of assessment programs can be viewed and used in very different ways. Over time, this can result in a disconnect between the methods used for assessment and the use of the results such that validity becomes an increasing issue.

## 4.3: Identifying the Desired Impacts – What do Governments Want for their Money?

The public is generally supportive of their taxes being used to fund scientific research: Pew Research Centre (2015) found that just over 70% of American adults agreed that government investment in engineering, technology and basic scientific research usually pays off in the long run, with around 60% believing that government investment is vital for ongoing scientific progress. In the United Kingdom, just over 80% agree that science makes people's lives easier with slightly less (76%) believing scientific research directly contributes to the country's economic growth. A similar number (79%) believe governments should fund scientific research, even in the absence of immediate benefits, and a large proportion (65%) do not think government funding should be decreased just because there are 'better' areas to spend the money (Castell, Charlton, Clemence, Pettigrew, Pope, Quiqley, Navin Shah and Silman, 2014).

One would expect similar results in most developed democracies. This does not change the fact that governments are custodians of public monies and have an obligation to their constituents to use that money responsibly and ensure they are pursuing maximum value for money. During times when national budgets are under pressure, this obligation becomes more pressing, especially when public confidence in science appears to be declining in some countries (Price &

Peterson, 2016). But with a high-risk, long term investment such as research, where the pathway from inception to impact is not always clear, how do governments sell research investment to the public? According to Mazzucato (2013), when under fiscal stress, governments need to be bold and increase spending on research and innovation related activities, yet this may be unpalatable to the public in the face of spending cuts to services. How do politics and policy interact to influence funding decisions?

Government support of research is often couched in terms of problem solving, reducing costs, new products and industries and skills development. ICT research in particular may play a key role in innovation policy and in many countries there is tacit recognition that in order to be able to fully access the global pool of new knowledge one must also be contributing to it.

Many countries have formulated research priorities based on supporting social, environmental, cultural and economic themes considered important to the community. For example, Australia has nine national Science and Research Priorities: Food; Soil and Water; Transport; Cybersecurity; Energy; Resources; Advanced Manufacturing; Environmental Change; and Health[4]. Priority areas in the United Kingdom include: Digital Economy; Energy; Global Food Security; Global Uncertainties; Living with Environmental Change; and Lifelong Health and Wellbeing[5]. Governments will therefore expect that a significant portion of the research they fund will contribute to these themes. These priority areas tend to be very broad, share a high degree of commonality across countries and are expressed in terms easily accessible to the general public.

Mazzucato (2013) takes this a step further, arguing that the higher rate of commercialisation of government funded research in the US compared to that in Europe relates to a greater use of 'mission oriented' funding of basic research (through agencies such as DARPA) rather than funding for 'general advancement'. Obviously there is a role for government to play in shaping research and selecting areas to preferentially support. The US experience has

---

[4] http://www.science.gov.au/scienceGov/ScienceAndResearchPriorities/Pages/default.aspx, accessed 4th May 2016

[5] http://www.rcuk.ac.uk/research/xrcprogrammes/, accessed 4th May 2016

shown that having large-scale, focused research agendas can lead to significant pay-offs in terms of the economy, security and global leadership.

Governments expect the nation will receive value for money from the research it funds. What is currently in flux is how this value is defined. As we move from value largely being based on excellence (as defined by the academy) to impact (the definition of which is still being resolved, along with who determines it) so too will the specific expectations of research funders and other stakeholders change.

## 4.4: Types of Impact

The majority of researchers hope that their work will have an impact – that it will be shown to make a difference in some way. Stakeholders are increasingly looking for the research they support to have maximum impact in the public sphere. But any policy or program specifying impact as an outcome has to think carefully about what type of impact they are looking for, how that impact can be measured or assessed and the possibility that some types of impact might be mutually exclusive.

Generally speaking, there are four main types of direct impact sought by funding bodies each with differing methods of assessment that have varying degrees of maturity: Discipline, Economic, Societal and Environmental.

The ways in which research can have an impact are nearly as varied as the research itself, but for our purposes impact largely falls in to one of these four broad categories. Each of these has their own challenges when it comes to measuring and assessing impact. The reality is that economic, social and environmental outcomes are closely intertwined, with each often indirectly affecting the others.

### *4.4.1: Discipline*

Discipline impact can be defined as the impact that a piece of research work has within the academy – the effect that it has on other research activities. A definitive proof can open up or close off other avenues of research. A new method or algorithm can be incorporated in to others work.

Research is a largely cumulative endeavour – building continuously on discoveries that have gone before. In the academic community, this previous work is acknowledged by citation. While citation practices may vary between disciplines, an influential piece of work will generally have a high citation rate compared to others within the same discipline.

Programs which assess discipline impact often label it as *Research Excellence*, or *Research Quality*, the assumption being that the excellence of an individual research outcome correlates with the influence it has on other practitioners. For all funding bodies the pursuit of research excellence will be a fundamental goal, even if it is not explicitly tied to the means by which they assess their programs.

Funding programs assess excellence both *a priori* and *a posteriori. A priori* assessment occurs as part of the selection process to decide which research proposals will receive funding. Funding is often awarded based on the quality of the individuals (their track record) and the perceived quality of the approach to be taken to a research problem, with peer review usually playing a significant role. *A posteriori* assessment of research excellence is often undertaken using citation analysis and peer review panels. Research excellence and methods of assessing it shall be discussed further in Chapters 5.3 and 7.1.

### *4.4.2: Economic*

> *"No matter how much science and technology may add to the quality of life, no matter how brilliant and meritorious are its practitioners, and no matter how many individual results that have been of social and economic significance are pointed to with pride, the fact remains that public support of the overall enterprise on the present scale eventually demands satisfactory economic measures of benefit."*
>
> – Chalmers W Sherwin & Raymond S Isenson, Project Hindsight, 1967

The undertaking of research can be a very expensive exercise. When competing for scarce funds, economic impact provides a powerful argument for investment, raising the possibility of being at least cost neutral in the long run, as well as contributing to efficiency and productivity goals. Economic impact is often process or product driven, resulting in cost reductions or the development of new income streams (goods or services).

Economic impact assessments are much loved by those who control the purse-strings – Treasury and Finance Departments and the like. This is quite understandable given the fiscal pressures on governments and companies. Even if public funding bodies assess their own programs from the perspective of research excellence they will usually have to make sound economic analyses to justify their allocations.

Over the last twenty years there has developed an industry of consultants and assessors providing services and tools for determining potential and actual economic impact utilising myriad models and methodologies. Tassey (2003) suggests a common method for assessing the economic impact of research is an impossible goal:

> *"The technology trajectories and economic outcomes that government programs or projects seek to leverage vary significantly, as do the complex economic structures that characterize a technology-based economy. Thus no single metric or measurement method can (1) address the diversity and complexity of an R&D agency's technological outputs, (2) describe the subsequent processes by which private sector impacts occur, and then finally (3) accurately capture the resulting economic outcomes."*

If this is true of economic impact, then how much more so of overall research impact?

In many countries, a significant proportion of publicly funded research is undertaken in the higher education or university sector. Not all research will, nor can be expected, to lead to direct economic outcomes. Significant work already exists on the impact of individual universities on their local and regional economies. For example, the University of California, Los Angeles, has an estimated annual contribution to Southern California of 95,000 jobs, USD$1.8 billion in tax revenues across all levels of government, with every $1 of direct expenditure by the university resulting in another $1.26 of economic activity and for every directly supported employee, creating an additional job in the region (Centre for Strategic Economic Research, 2015). The University of Birmingham is considered to have value-added in excess of £500 million to the West Midlands economy in 2011/12 (Oxford Economics, 2013). Glasgow University contributes more than £600 million of gross value added and 15,000 jobs to Scotland's economy (University of Glasgow, 2016). Canada's University of Ottawa is calculated to have a total annual economic impact of between CAD$6.8 and $7.4 billion, including over $1.5 billion to Canada's GDP (Conference Board of Canada, 2015), while the University of Toronto contributes in excess of $15 billion annually to the national economy (University of Toronto, 2013). John Hopkins University and its associated health services accounted for more than USD$9.1 billion in economic outputs and 86,500 jobs in Maryland alone during 2014 (Appleseed, 2015).

Of course, the economic impact of universities is derived from more than their research activities and for many, one would expect that the indirect effects resulting from students electing to move to the area for study would be one of the most significant factors. Nonetheless, research activities can contribute to institutional reputation, attracting enrolments. Under the right conditions universities can also attract the formation of industry clusters.

Not every item of research work can, nor should be expected to, deliver an easily measurable direct economic impact. We also know that useful outcomes are not guaranteed from research activities – it is inherently high risk. Because of this, those research activities that do have a large economic impact make interesting case studies, but may not necessarily enlighten us as to how to replicate the success. Ultimately, economic impact as it applies to individual research activities may not tell us much that is new. However, if you are lucky, you will have a small number of success stories that demonstrate a significant economic return from research is possible. For example, in 2015, Cochlear Ltd, the company which commercialised Graeme Clark's pioneering research in cochlear implants for the hearing impaired, had global revenues of $925 million, more than 2,600 employees world-wide and a market capitalisation value of $4,565 million[6]. In that same year, the company was liable for $37 million in income tax and contributed $243 million to economic activity via employee salaries and wages. Over the ten years 2006 to 2015, Cochlear Ltd generated more than $7 billion in revenue (Cochlear Ltd, 2016). During the same period the Australian Commonwealth Government averaged annual research and development expenditure of $8.7 billion across all portfolios (Department of Industry and Science, 2015), suggesting that the research underpinning Cochlear's activities has generated an almost 10% return on the country's investment in all research over the period. To date CSIRO has received more than $430 million in revenue from patents relating to its contributions to wifi technology[7], just one of many commercial outcomes from its research. The CSIRO developed BARLEYmax cultivar is estimated to provide improved health outcomes worth more than $300 million per year for Australia, including a projected annual $17 million savings in health costs, in addition to increased farm income and new food products[8].

Cochlear Ltd and CSIRO are examples of publicly funded research in Australia ultimately having an economic impact. It is unrealistic to expect all, or even a significant portion of, research to have a similarly measurable direct impact. When considering information and communication technologies, it is not only possible to generate significant income or savings, but to also disrupt the way in which business is conducted.

### *4.4.3: Societal and Social*

The identification of potential societal or social impact is required of some research funding programs. For example, the US National Science Foundation

---

[6] http://www.cochlear.com/wps/wcm/connect/intl/about/investor/financial-history, accessed 9th June 2016

[7] https://csiropedia.csiro.au/wireless-lans/, accessed 9th June 2016

[8] http://www.csiro.au/en/Research/AF/Areas/Plant-Science/Wheat-barley/BARLEYmax, accessed 27th July 2016

(NSF) requires that the Project Summary for full applications contains separate statements regarding intellectual merits and broader impacts of the proposed research. The NSF defines intellectual merit as the potential to further advance knowledge (effectively discipline impact), while the broader impact statement is based on the potential benefit to society and contribution to specific, desired societal outcomes (National Science Foundation, 2013).

Linking research to specific potential societal outcomes is not always easy, nor is defining what a societal outcome actually is. Early versions of the application guide provided guidance to reviewers in the form

> "*How well does the activity advance discovery and understanding while promoting teaching, training and learning? ……broaden the participation of underrepresented groups…? To what extent will it enhance the infrastructure for research and education…..? Will the results be disseminated broadly to enhance scientific and technological understanding? What may be the benefits of the proposed activity to society?*" (National Science Foundation, 2009).

These early NSF guidelines resulted in potential impacts relating to education, training, mentoring and the development of research infrastructure predominating in applications. This is a long way from Bornmann and Marx's (2014) assertion that societal impacts occur when the outputs of research move out of the academy and are addressed outside science.

In their <u>Guidance for Applicants</u> the UK Medical Research Council suggests societal impact includes

> *"Increasing the effectiveness of public services and policy. Enhancing quality of life, health and creative output"* (2016).

Thus, as a body primarily concerned with health research, the incorporation of research into policy and practice guidelines is an important indicator of societal impact. Following on from Donovan (2008), Bornmann (2012) distinguishes between societal and cultural benefits thus:

*"'societal benefits' refers to the contribution of research to the social capital of a nation, in stimulating new approaches to social issues, or in informing public debate and policy-making. 'Cultural benefits' are those that add to the cultural capital of a nation, for example, by giving insight into how we relate to other societies and cultures, by providing a better understanding of our history and by contributing to cultural preservation and enrichment."*

This distinction suggests societal benefit is predominantly achieved via the influence of research on institutions and political processes, whereby cultural benefit has a higher proportion of impact occurring via influence on individuals. If we consider societal or social impact to occur when there is either an influence on individual behaviour or on social policies (which in turn aim to influence individual behaviour) this distinction may become irrelevant.

Attempts to define societal impact for the purposes of research assessment would appear to be placed on a continuum between a general inclusion of any impacts which occur outside of the academy and a restrictive notion of policy and practice impacts. Under the former, economic and environmental impacts are included as societal impacts, while the latter focuses on utilising pathways to impact, which are notoriously difficult to achieve.

Societal or social impact therefore is difficult to define, with most studies focused on identifying the interactions and pathways by which it occurs, rather than the actual impact. There are three main ways in which this type of impact is thought to occur (Bornmann, 2013; de Jong, Barker, Cox, Sveinsdottir and Van den Bessalar, 2014):

1. Via knowledge embedded within a *product* – such as information, tools, methods, models, instruments, products. De Jong et al (2014) suggest summaries provided for policy makers by the Intergovernmental Panel on Climate Control of the Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation report as an example of this way in which research can have societal impact.

2. Via knowledge *use* – where interactions between researchers and other members of society result in the use of the knowledge in society. Examples of this can include the implementation of policy recommendations arising from research or when researchers act as consultants.

3. Via *social benefits* – de Jong et al (2014) define this as being the effects of the use of research results and this can be changes in policy, professional practice, culture, business activity, employment, education or community involvement.

As the definition of societal impact is unfixed, so too is the notion of preferred indicators. Bibliometric comparisons between disciplines are fraught with danger due to differences in dissemination and citation practices, and it may be that a similar situation arises when trying to compare societal impacts. As the Research Council of Norway notes

> *"The societal impact of research spans a wide range, from short-term economic gain to influencing how human identify is formed."* (2015)

suggesting metrics and indicators may be of limited use. Of concern is that there would appear to be a conflation occurring between social impact and social awareness as indicated by metrics focused on social media activity, often referred to as *altmetrics*. Altmetrics will be discussed further in Chapter 7.6.1 but for the moment it is sufficient to note they are predominantly an indicator of the amount of awareness concerning a piece of research rather than of any effects resulting from the application of the work.

Some examples of societal impact are relatively easy to identify: outcomes from research can feed in to public policy, regulatory changes or best practice guidelines. With the exception of regulation, behavioural changes resulting from these implementations can take significant time to become apparent. Like the majority of research impacts, the ability of researchers to influence this impact is limited. Policy recommendations often have to take a back seat to political considerations. Regulation recommendations can be defeated by lobby groups with vested interests.

Even more so than other types of impact, assessment of societal impact may be in the eye of the beholder. Internet and mobile data-based technologies have dramatically changed the way that individuals interact across all aspects of society. While this is easy to recognise, it cannot be quantified in a meaningful way and for every parent who celebrates their awkward child being able to find a peer group on line there will be another bemoaning their child's difficulty in engaging in with a person standing in front of them rather than their smartphone. Change is not experienced in the same way by everyone, and while the benefit to society overall may be positive, any individual, or group, may have a very different experience. Technological advances can be particularly prone to this. Increased automation may provide more efficient and inexpensive goods and services for the majority of society, but it can also result in the loss of secure, well-paid jobs for large numbers of workers, many of whom will find it difficult to continue accessing meaningful employment.

Broader impact has been assessed in the NSF application process by the same group of peers assessing intellectual merit, raising the question posed by Bozeman and Boardman (2009) – why are the scientists more qualified to make judgements on what is good for society than any other person in the street? Derrick and Samuel's (2016) study of the experiences of evaluation panel members in the 2014 UK REF assessment suggests those being asked to undertake this assessment are not necessarily confident in their ability to do so, reinforcing the importance of the question of who should be doing the assessing. This issue is particularly important when potential for wider research impact is considered as a factor when awarding funding. Pollitt, Potoglou, Patil, Burge, Guthrie, King, Wooding and Grant's (2016) study of the general public and researchers preferences in regards to desired health and biomedical research impacts suggests while there are some commonalities, there are also differences in the types of impacts that are valued by each group. These findings demonstrate the need for further investigation of the question of who should be assessing impact, both prior to and after funding.

#### *4.4.4: Environmental*

Direct environmental impacts will generally be relatively easy to assess, based as they are on easily observable and quantifiable outcomes: a decrease in certain pollutants measured in waterways; an increase in the population of a targeted species; reduced water usage for processes. But while there is a significant body of research undertaken across a multitude of disciplines focused specifically on environmental issues, research in other areas can also indirectly lead to environmental impacts, both good and bad. Health research that identifies a particular compound as a cause of birth defects can prompt improved industrial emission standards leading to lower pollutant levels in the environment. As noted by Pencheon (2011), health research that leads to people undertaking more physical activity will help to decrease obesity but is also likely to contribute to lower usage of fossil fuels for short-trip transportation. Not all environmental impacts will be positive. Ongoing research that results in rapidly improving electronics can lead to increased waste as consumers embrace a rapid turnover of products to ensure they always have the latest gadget. As European Commission guidelines regarding research and innovation policy impacts notes, there are

> *"… direct and indirect links between public intervention in research and innovation (R&I) with environmental pressures and impacts. … in order to attribute environmental impacts to public intervention in R&I, there is a need to identify relevant tangible and intangible outcomes and socio-economic impacts of R&I policy. The latter lead (directly or indirectly) to environmental pressures and impacts."* (Miedzinski et al, 2013)

Just undertaking research has an environmental effect in itself, with some facilities being particularly impactful. The CERN large hadron collider utilises 1.3 terawatt hours of electricity each year, the equivalent of powering 300,000 homes for the same period[9]. Animal research facilities generate significant amounts of waste, including hazardous waste, in addition to consuming large amounts of resources (Groff, Bachli, Lansdowne & Capaldo, 2014).

[9] http://home.cern/about/engineering/powering-cern, accessed 6th June 2016

Full assessment of environmental impacts associated with any research activity is therefore going to be a complex task.

## 4.5: The Tyranny of Timeframes – Taking the Long View

Research is inherently a high-risk activity – there is no guarantee that any problem-directed research will find a solution, let alone one that is timely, affordable, and implementable. Time frames are a major challenge when attempting to assess impact.

Impact follows on from the production of research outputs – conference papers, journal publications, books, patents and the like – which disseminate the research findings. When considering the effectiveness of new funding programs one has to take in to account the time required to assemble and establish the research team and facilities, undertake the work and then prepare for dissemination. Of course, very few research activities start from an entirely zero position, but there still must be a time lag before outputs are produced. Daim, Monalisa, Dash and Brown (2007) found that for the then emerging field of nanotechnology, while conference papers began to appear almost immediately after funding began to flow, journal articles took two to three years to begin appearing and it was five to six years before patents began to be issued.

In developing their method for measuring the length of time required for biomedical research to be translated into improved health outcomes, Hanney et al (2015) found there was considerable variation in the point in the R&D continuum that the time frame was measured from. The seven case studies they examined, involving pharmaceutical, screening public health, psychosocial and service delivery outcomes, indicated times to impact of between 18 and 54 years. This included a time frame of between 0 and 17 years to move from the initial discovery to commencement of initial phase one trials or human research. It is not unexpected that the translation of medical research into measurable outcomes requires long time frames, but this study does illustrate two of the difficulties involved with developing impact assessment frameworks

– selecting an appropriate time frame and how to identify start and end points on the R&D continuum.

The relatively long time for impact to become apparent is not always limited to medical breakthroughs with their associated need for safety and efficacy trials prior to introduction to the community. Adams' (1990) comparison of scientific activity across a number of fields and productivity growth in the USA found

> *"…, a lag in effect of roughly 20 years is found between the appearance of research in the academic community and its effect on productivity in the form of knowledge absorbed by an industry."*

Adams (1990) did find that the time lag for academic technology was far less than that for academic science: approximately ten years compared to thirty and it would not be surprising to find that the speed of technology impact is increasing.

In 1998, Mansfield reported that across seven industry sectors it took 6.2 years for academic research undertaken within the previous fifteen years to be introduced commercially as a new product or process and 5.1 years for innovations that were developed with 'very substantial aid' from research over the same period. This represented a decrease on the time lags reported for academic research undertaken over the period 1975 to 1985 (Mansfield, 1991). Mansfield (1998) does not attempt to identify the reasons for this decrease but does note if it is due to a quicker utilisation of academic research findings then it could be of considerable economic benefit, but if it is a result of academic research moving towards more applied and short-term research then the long term implications could be quite different.

Analysis of 2014 UK Research Excellence Framework (REF) case studies suggests that the time for impact to become apparent is between three and nine years, depending on the discipline (King's College London and Digital Science, 2015). The authors do note this time calculation must be approached with caution as it may be a function of the way in which the assessment was undertaken. While institutions were able to submit case studies based on research undertaken from 1993 onwards, the majority of submissions cited research that had been published in the years since 2008. In suggesting this may also be a result of the selection and production process, King's College London and Digital Science (2015) point out that further investigation is required as to why this happened. It may be as simple as a lack of corporate memory. Many researchers involved in earlier research may have left the institution and in those earlier years there would not have been the same incentive to capture examples and evidence of research impact as there is now.

Citation analysis shows that time frames can also be difficult when attempting to assess impact within the academic community. Depending on the discipline, papers take varying amounts of time to reach their peak citation rate and will stay at that level for varying times (for example, Wang, 2013; Radicchi & Castellano, 2011). There are suggestions that even within the same field, individual journals exhibit different citation distribution patterns (Moed, van Leeuwen & Reedijk, 1998). Chakraborty, Kumar, Goyal, Ganhuly and Mukherjee (2015) identified six distinct citation pattern profiles associated with 1.5 million papers relating to computer science. Taking a macro approach of examining *Web of Science* data from 1900 to 2006, Wallace, Larivière and Gingras (2009) showed that the average number of citations received by papers within two- and ten-year citation windows has increased over time. While it is tempting to attribute this to an increase in the quality and collaborative nature of modern research, it is just as likely to be attributable to the greater amount of research being undertaken and the increased size of the community.

It is thought that most highly influential papers reach their maximum rate of citation between two and six years after publication before tailing off (Bouabid, 2011). But there are also instances where a publication receives very little attention in those first years before experiencing a relatively sudden increase in citations. Given the name 'sleeping beauties', these papers are believed to be ahead of their time (van Raan, 2004). Initially thought to be very rare at around one in ten thousand papers (van Raan, 2004; Marx, 2014), the occurrence of sleeping beauties is more common in certain disciplines (notably physics and chemistry, where they may be higher than 7%) and they can sleep for significant periods of time – more than thirty years (Ke, Ferrar, Radicchi & Flammini, 2015). It has also been reported that in some fields, more than half of the 'sleeping beauties' have an applied focus (van Raan, 2015), suggesting they can be an important source of innovation. Ke et al (2015) found that, despite limitations,

> *"… papers whose citation histories are characterized by long dormant periods followed by fast growths are not exceptional outliers, but simply the extreme cases in very heterogeneous but otherwise continuous distributions."*

Reasons for the awakening of sleeping beauties are likely to be as varied as the sleeping beauties themselves. Ke et al (2015) report that for many sleeping beauties most of their citations come from other disciplines, suggesting that a different context is found for the work in a new discipline. Wang, Ma, Chen and Rao (2010) suggest the increasing visibility of and access to research papers via the internet as more archives become digitised may also play a role and it is certain that literature searches produce more comprehensive results in the internet age.

What cannot be denied is that sleeping beauties can be incredibly important and can sleep for a long time. The most commonly cited sleeping beauty is Mendel's work on plant genetics, ignored for thirty-four years, with the phenomenon sometimes referred to as the Mendel Syndrome (van Raan, 2004). The 1961 paper introducing the Shockley-Quiesser Limit, a fundamental limit on the conversion of sunlight into electrical current, shows an annual citation pattern that mirrors the growth in solar power related research, increasing exponentially since 2000 (Marx, 2014). In 1994, Takeda and Shiraishi published a theoretical model of a flat hexagonal atomic structure for silicon, which has seen its citation rate increase dramatically in the last five years as research in graphene and silicone sheets has taken off (van Raan, 2015). Van Calster (2012) reports that Peirce's 1884 Science paper on evaluating a prediction system averaged less than one citation a year until the year 2000, when it increased to 3.5 per year before reaching 10.4 for the years since 2010.

In examining this change, Van Calster (2012) notes the increase in citations is spread across a number of disciplines and suggests that

> *"This citation increase in various domains may be attributed to a widespread, growing research focus on mathematical prediction systems and the evaluation thereof. Several recently suggested evaluation measures essentially reinvented or extended Peirce's 120-year-old ideas."*

This accords with the suggestion by Ke et al (2015) that work finds a new audience through application in a new field.

It is not only the length of the time frame being examined that influences the perceived impact of a piece of research, but also the point in time at which the assessment is being undertaken. Penfield, Baker, Scoble and Wykes (2014) suggest the research behind the development of thalidomide provides an example of how the judgement associated with impact assessment can change over time. In the aftermath of the thalidomide scandal in the 1960s it would be difficult to find people who disagreed with the statement that while the drug had a significant impact, it was overwhelmingly negative. Yet in recent years, thalidomide has shown promise as a targeted treatment for cancer and has greatly improved the lives of leprosy sufferers. The way in which we view thalidomide and its impact has become more nuanced over time and this is likely to hold true for a number of research outcomes.

A related issue in regards to timing is that of what other technologies are being developed at the same time. Some innovations need to be paired with others to achieve their full impact. The internet is considered to have its beginnings in the US Advanced Research Projects Agency Network (ARPANET), established in 1969 as a way of maximising the return on expensive resources:

> *"Computers weren't small and they weren't cheap. Why not try tying them all together? By building a system of electronic links between machines, researchers doing similar work in different parts of the country could share resources and results more easily. Instead of spreading a half dozen expensive mainframes across the country devoted to supporting advanced*

> *graphics research, ARPA could concentrate resources in one or two places and build a way for everyone to get at them. One university might concentrate on one thing, another research center could be funded to concentrate on something else, but regardless of where you were physically located, you would have access to it all."* (Hafner & Lyon, 1996).

Starting with four computers, by the late 1980s ARPANET was one of hundreds of interconnected networks (the internet), with use largely confined to parts of the scientific and academic communities (Hafner & Lyon, 1996). It took Tim Berner Lee's invention of the World Wide Web at the turn of the decade before the internet began to change the way the world does business, socialises and shares information.

This is an example of a highly disruptive technology which is actually a combination of technologies. As noted by the National Research Council (2010) the most disruptive technologies arise when two or more well-understood technologies are integrated into a new technology or application, often where no relationship has previously been identified. Examples of this phenomenon include the modern internet, digital photography, smartphones, personal computers and improvised explosive devices (National Research Council, 2010).

Video and audio streaming are new industries which are proving to be highly disruptive to established business models for the sale and distribution of music and movies and those that underpin television and radio with their dependency on being able to deliver consumers to advertisers. As Berger and Frey (2015) point out, the emergence of this new industry was only possible due to the simultaneous development of a number of technologies addressing issues limiting its desirability as a consumer product: bandwidth, computing power, graphics quality and internet reach.

Instances where impact is dependent on the convergence of a number of factors (not all of which need to be technical) is an important example of researchers having little influence on the final impact of their work, and of the difficulties in predicting just what is likely to have impact.

## 4.6: Competing Impact Areas

It has been suggested that increased emphasis on indicators such as impact factors and citation rates by research funding agencies and promotions committees may lead to a reluctance to patent, and hence protect, publicly funded research (Suhbrier & Poland, 2013). There has also been concern expressed that a focus on patenting leads to diminished publication activity. In reality, several studies have found that patenting academic researchers tend to publish more than non-patenting researchers and, while not necessarily a strong association, these researchers may also be publishing work of higher quality as measured by citation analysis (Grimm & Jeanicke, 2015; Tsai-lin, Chang & Katzy, 2014; Wang & Guan, 2010; Azoulay, Ding & Stuart, 2009). In the growing biotechnology field it would seem publications which can be linked to a patent are more highly cited, with their authors generating higher *h*-indexes (Magerman, Van Looy & Debackere, 2015). It should be noted that Wong and Singh (2010) found the relationship between patenting and publication appears to vary between regions with both quantity and quality of publications being important for North American universities, only the quantity of publications being important in Europe, Australia and New Zealand, while for universities outside these areas only the quality of publications is important.

While encouraging, this relationship between patenting and publication quality may be a case of correlation rather than causation. Are highly productive researchers (both in terms of quantity and quality) just more likely to patent as a result of producing greater numbers of ideas, the same proportion of which are good? Are there other factors at play? United Kingdom data suggests researchers who undertake their training at universities with established technical transfer resources and cultures tend to produce more patents over the course of their careers (Lawson & Sterzi, 2014). Lawson and Sterzi (2014) posit that this 'social imprinting' during PhD training is more important than the patenting culture in which the researcher is actually working at any given time and that when coupled with early success in patenting and commercialisation results in better quality patents. This accords with Tartari, Perkmann and Salter's (2014) assertion that attitudes towards engaging with industry are heavily influenced by departmental peers, with this influence being strongest on junior department members.

A number of studies have shown women tend to publish and patent less (for example, Ding, Murray & Stuart, 2006; Whittington & Smith Doerr, 2005). In line with this, Irish research has found that women are 40% less likely than men to expect that their work will result in commercialisation activities (Ryan, 2012). McMillan's (2009) findings that, while less in number, women's patents tend to be of higher quality than men's, may reflect a higher standard being set for women when considering patenting (whether by the researchers themselves or others). The reasons behind women's tendencies to not patent and seek commercial outcomes are likely to be many and varied, as are those for men who do not. It is conceivable that perceptions concerning potential competition between impacts may have a role for some people. If someone believes they have to make stark choice between publish or patent, their choices will be influenced by their career and economic goals, along with the likelihood of eventual success.

Concerns have been expressed regarding the effect of patenting and working with industry (which is often an expression of economic impact) on aspects of university research such as quality, direction, and openness of dissemination. In common with many other aspects of the research and innovation ecosystem, studies have shown mixed outcomes, sometimes positive, sometimes negative and sometimes neutral (for example: Louis, Jones, Anderson, Blumenthal & Campbell, 2001; Gulbrandsen & Smeby, 2005; Geuna & Nesta, 2006; Dietz & Bozeman, Thursby & Thursby, 2011; D'Este, Tang, Mahdi, Neely & Sanchez-Barrioluengo, 2013). This variation in outcomes may be a manifestation of Banal-Estañol, Jofre-Bonet and Lawson's (2015) finding that for UK engineering academics, the effect of increasing industry collaboration on publication rates is inversely curvilinear, such that maximum publication rates occur when academics spend some, but not all, of their research time on projects with industry involvement.

D'Este et al (2013) report that at the departmental level engagement with industry has no systemic effects on research quality and postulate that across disciplines

> *"… the relationship between academic excellence and engagement with business is largely contingent on the institutional context of the university department."*

That is, some departments are able to maintain (and even improve) scientific excellence while simultaneously engaging with industry, but others find this difficult and may have to choose between pursuing one or the other. A university department is made up of a cohort of academics, students and support staff, operating within the norms and frameworks of both their discipline and the university of which they are a part.

Similar to Lawson and Sterzi's (2014) findings regarding the influence of the training environment on future patenting levels, Salami, Bekkers and Frenken's (2015) study of a Dutch cohort found that students who undertake their PhDs in collaboration with industry tend to publish more and have higher overall numbers of citations than their peers (although citation per publication may be slightly lower). Not surprisingly, they also have higher levels of participation in patenting activities (Salami et al, 2015).

All of this suggests that while discipline impact (as evidenced by scientific excellence) and economic impact (as evidenced by industry engagement) can be competing priorities, they do not have to be. There are ways for researchers to pursue both, but their ability to do so successfully will be highly dependent on the environment in which they undertook their training, the environment in which they work and the cultural mores and support mechanisms of that environment.

For researchers who are enthusiastic about public engagement and popularising science as a way of having impact there may also be competing priorities. Named after Carl Sagan's apparent rejections by Harvard and the US National Academy of Sciences, the Sagan Effect refers to the perception that science popularisation is done by second-rate scientists - that it is not possible to be both academically rigorous and to have a high public profile. At least, not until after you have received your Nobel Prize. Martinez-Conde (2016) suggests this perception is rooted in the idea that research is a vocation:

> *"According to this view, the ideal academic worker is devoted solely to the pursuit of knowledge and associated work in the lab, without external interference. … deviating too much from the idealized image of the single-minded, focused academic is still considered problematic."*

Yet studies have also suggested that academics who engage in dissemination beyond academia to the wider community can be both more productive and higher ranking than those who do not (Bentley & Kyvik, 2011; Jensen, Rouquier, Kreimer & Croissant, 2008). Public engagement does appear to be more acceptable for established researchers than those in the early stages of their careers (Jensen et al, 2008; Martinez-Conde, 2016) but given the increasing emphasis on public engagement by funding bodies there needs to be encouragement given to researchers at all stages to become involved. It would be fair to say that, despite the growth of the triple-helix model of the university in recent years, public engagement is rarely considered on an equal footing with research and teaching when it comes to appointments and promotions. Until this changes, public engagement as a form of creating impact will only be undertaken by those who are highly self-motivated or secure in their career path. In recognition of the increasing role of public engagement in academic life the American Sociological Association recently released a framework to support the use of evaluation of public engagement when considering promotion or appointment (2016). This is an important conversation for the research community to have. Maintenance of the research enterprise is heavily reliant on the work routinely undertaken by researchers in their own time and creating additional expectations without providing incentives, resources or time to support them are unlikely to be sustainable.

We can see conflicts between economic and environmental impacts being played out in media outlets across the globe. Protestors face off against bulldozers, court proceedings seek to impose restrictions or bypass objections. Sometimes, social impacts can also play a large part in these disputes – dams which require the re-location of established villages; factories which expose surrounding residents to dangerous pollutants. While initially technology research would appear to be far removed from these types of conflicts, there is a connection.

Much ICT technology, particularly at the consumer level, is subject to continual improvement and rapid turnover. On average, in the USA and UK, mobile phones are replaced every two years or less (Entner, 2011). For significant numbers of people it is natural to upgrade mobile phones, tablets or computers on an annual basis. This rapid turnover of devices results in environmental pressures at both ends of the lifecycle. Precious metals such as palladium, platinum, gold and silver are used in the manufacture of ICT technologies, along with the more common copper, aluminium, tin, zinc and iron. Every ton of mobile phones contains around 3.5kg of silver, 340g of gold, 140g of palladium and 130kg of copper. (Schluep, Hagelueken, Kuehr, Magalini, Maurer, Meskers, Mueller & Wang, 2009). While the amount contained in individual items is minute, in 2007, 1.2 billion mobile phones were sold globally (Schluep et al, 2009). The US Environmental Protection Agency (EPA) estimates that 35t of copper, 350 kg of silver, 34 kg of gold and 14 kg of palladium are recoverable from every one million smartphones[10]. The requirements for these materials places increased demands on the environment through the expansion of mining and processing operations to meet demand.

At the other end of the life cycle there is a growing e-waste problem, one that is often exported from developed nations and leads to the contamination of soil and water, along with associated health problems. Toxic components of computers include lead, mercury, cadmium, fire retardants and plastics which give off noxious gases when burnt (Venkatraman, 2011). Thus there is an inherent tension in much ICT hardware research. That which leads to improved and cheaper consumer devices is also likely to lead to increased pressure on

[10] https://www.epa.gov/recycle/electronics-donation-and-recycling, accessed 25th September 2015

resources and potentially negative impacts on the environment, and those who live and work in it.

## 4.7: Searching for Additionality

As noted by Loi and Rodrigues (2012),

> *"The aim of policy evaluation is to measure the causal effect of a policy on outcomes of interest, on which it is expected to have an impact. The policy's causal effect is defined as the difference between the outcome of the units affected by the policy (the actual situation) and the outcome that these same units would experience had the policy not been implemented. The fundamental evaluation problem is that we cannot observe simultaneously the same unit in the two scenarios, i.e. the scenario in which the policy is not implemented – the counterfactual – is an elusive one to produce or simulate."*

They then remind evaluators that just comparing before and after, or those who have and have not interacted with the policy, will not adequately identify the actual causal effects arising from the policy intervention (Loi & Rodrigues, 2012).

The causal link between a policy or program intervention is fundamental to the idea of additionality – the outcomes of the intervention must not have been going to happen anyway. At the very least there needs to be a change in the time frame within which an outcome occurred. The most succinct way to express this is the simple question – "what difference did it make?"

In recent decades input and output additionalities have tended to be the focus of policy intervention evaluations on the basis that unsuccessful interventions are those that do not create more inputs and/or outputs than would have been created without the intervention (Gök & Edler, 2012). On the input side, a common example of intervention aimed at additionality is found in numerous studies attempting to determine if the provision of subsidies results in companies spending money of their own on R&D that they may not have otherwise. The use of patenting subsidies to increase levels of patenting provides an example of programs focused on output additionalities. Behavioural additionality adds a level of nuance to this evaluation. Largely concerned with persistence, behavioural additionality also considers changes in the way actors operate and learnings they have taken forward from their participation in the program (Gök & Edler, 2012).

Additionality without identifiable causality is merely association or correlation. But given the number of factors acting on research and its outcomes, determining causality is notoriously difficult. Add to this the often non-linear route from research outputs to impacts and the challenges facing program evaluators become apparent.

In the absence of randomised experiments and adequate control groups, one established method of dealing with this question of causality and additionality is through the use of statistical inference tools such as counterfactual analysis, Bayesian analysis, Markov models, and structural causal and equation models (Pearl, 2009). Any analysis of research impact is likely to rely on myriad assumptions and be replete with data gaps, such that results can be subject to multiple interpretations. The diversity of the research environment and outcomes means that we are unlikely to ever have a standard suite of models and analyses for use. This does not mean that we should not keep refining the methods. Over time we would hope to become better at selecting the most appropriate method for the context.

## 4.8: Attribution – Deciding Who is Responsible

*"We are too much accustomed to attribute to a single cause that which is the product of several, and the majority of our controversies come from that"*

- Marcus Aurelius, Emperor of Rome, The Meditations, c170

Modern science is characterised by collaborations and increasingly the number of collaborators is growing. From 1960 to 2010 the average number of co-authors on physics, chemistry and mathematics papers increased, with physics experiencing particularly rapid growth after 1990 (Huang, 2015). Between 2007 and 2011 the average number of authors on papers recorded in the *World of Science* citation index increased from 3.8 to 4.5 (King, 2012). The proportion of single author papers has also been decreasing (Huang, 2015; Nabout, Parreira, Teresa, Carneiro, Ferreira da Cunha, de Souza Ondei, Caramori & Soares, 2015) and it is expected that within fifty years they will make up less than one in a thousand papers published in particular disciplines (Nabout et al, 2015). Global projects and international facilities such as the Human Microbiome Project and the Large Hadron Collider result in papers with hundreds and even thousands of co-authors. The growth in the number of authors per paper (often termed 'author inflation') makes more pertinent long-standing questions about the relative contributions of authors.

Conventions regarding the order in which author names are listed can vary greatly between disciplines, countries, journals and even laboratories (Brand, Allen, Altman, Hlava & Scott, 2015). The order can be simply alphabetical, the grant holder may be named first or last, the main contributor may be named first, with the laboratory head or most senior author named last. Some journals require a statement designating contributions, for example, 'Author A conceived of and designed the experiment, Authors B and C undertook the experimental work, Author C undertook the analysis and wrote the manuscript. All authors reviewed and approved the manuscript.' In some instances, not all of the authors listed may have actually contributed in accordance with journal guidelines. Tarnow's 2002 survey of more than 3,000 physicists around the world found levels of inappropriate authorship of between 23% and 59%, depending on the guidelines being applied. Tarnow (2002) also concludes that

> *"… it is generally not possible for a peer to determine who contributed the most from the information currently present in the byline".*

Inappropriate authorship, predominantly in the form of 'honorary' and 'ghost' authorship would also appear to be relatively common in biomedical journals (Kornhaber, McLean & Baber, 2015). Bozeman and Youtie (2016) suggest that problems with paper authorship are potentially more likely in cross-disciplinary research where cultural norms regarding inclusion and ordering as paper authors can be very far apart.

The academic literature is science and research's public record. It is the arena where ideas are challenged and tested and where an individual's contribution is formally acknowledged. When careers are highly dependent on publication records there can be significant pressure to increase your publication count, yet there is nothing in the way that authors are listed which can reliably tell us the size or importance of an individual's contribution.

Bozeman and Youtie (2016) report that geographical dislocation can be a contributing factor in researchers not receiving due credit as paper authors, and this can be a particular problem when someone has left the original research group. This can be a simple case of 'out of sight, out of mind', or more worryingly, a deliberate use of distance to disadvantage a collaborator.

When impact factor is being assessed for a piece of research undertaken a number of years previously, there is an increased likelihood of the contributors to that work being geographically dispersed. In some instances, there may be no members of the team remaining at the institution where the work was undertaken. If assessment is being directed at the institutional level, which would appear to be the emerging norm, who gets to submit the work? The institution where it was undertaken? The institution where the lead researcher is now employed? What if they have left the sector? Retired? Deceased? Should all the institutions where team members are currently employed be able to claim the impact? While it is not the case for all areas of research, there are many which would not be possible without specialist facilities and similarly, facilities require researchers who are able to fully exploit them. While it will not hold true in all cases, there are undoubtedly instances where institutional support is vital to seeing research through to impact.

The United Kingdom's Research Excellence Framework (REF) 2014 required researchers need not have been working at the institution submitting the impact on the census date, but they must have undertaken the underpinning research at that institution. Impact was assessed using case studies, and unlike the research outputs also being assessed, they were not linked to individual researchers (Research Excellence Framework, 2013). This approach allows for the influence the research environment itself will have on being able to achieve impact, but one can imagine that for universities where major impacts have been realised by staff who have since left there are challenges in building case studies.

As we shall see in Chapter 6, for research to have an impact outside the academy, the intervention of other parties is nearly always required. Just as invention and ideas require implementation to become innovation, so too does research require implementation to have impact. One could argue that those responsible for implementation are the ones to whom the impact should be attributed.

Collaborative work may result in a number of institutions wishing to claim the impact, particularly when there are monetary rewards involved. The 2014 REF includes impact case study submissions with the same title and submissions with very similar titles (Higher Education Funding Council for England, 2015a). In some instances, this is likely to be a result of basing the assessment unit on research fields rather than socio-economic objectives. For example, the University of Exeter submitted case studies on research which identified associations between exposure to bisphenol A (BPA) found in certain plastics and increased disease risks under three assessment units[11]:

1. Earth Systems & Environmental Sciences – Bisphenol A and its potential human health effects (CS37250);

2. Clinical Medicine – The plastics chemical Bisphenol A and its potential human health effects (CS35614); and

[11] www.impact.ref.ac.uk/Casestudies, accessed 24th August 2016

3. Biological Sciences - Bisphenol A and its potential human health effects (CS37307).

For the three case studies submitted, five of the six research papers referenced are the same across the studies, and similarly there are common shared grant support and corroboration sources listed.

In other instances, it will be the same piece of collaborative research submitted by the participating institutions that have not taken the opportunity to make a joint submission regarding the work. For example, within the Psychology, Psychiatry and Neuroscience unit of assessment, University College London and the University of Bangor submitted separate case studies on the development and evaluation of Cognitive Stimulant Therapy for use with dementia patients[12]:

1. University College London – Cognitive Stimulation Therapy – a new therapy for dementia (CS23095); and
2. Bangor University – Cognitive stimulation – an effective intervention to improve quality of life and cognition in people with mild to moderate dementia (CS21480).

The submitting universities have focused their case studies in slightly different ways, reflected in the research subject areas which they are associated with, and presumably, the research strengths each brought to the collaboration. University College London has tagged their case study as belonging to the Medical & Health Studies and Psychology & Cognitive Sciences subject areas, while Bangor University has selected Psychology & Cognitive Sciences and Economics. This difference in subject area focus is reflected in relatively small overlap in the referenced research and corroboration sources. Interestingly, it is University College London who notes that the economic analysis was undertaken in collaboration with the London School of Economics, while the Bangor University case study does not, even though it appears to have a greater stress on demonstrating the economic benefit of implementing the therapy.

[12] www.impact.ref.ac.uk/Casestudies, accessed 24th August 2016

While each party acknowledges the involvement of the other in the project it is not necessarily easy to determine how much attribution each should claim.

Attribution need not be an issue, depending on why you are undertaking the assessment. If your aim is to make a general case for taxpayers to keep funding research, then attribution is not overly important – it is enough to be able to show that an acceptable proportion of research has an observable impact on people's lives. If you are using the assessment to determine funding, or career paths, then it is much more important for attribution to be clear and accurate.

It has been suggested that research assessment needs to focus more on contribution rather than attribution (Spaapen & Van Drooge, 2011; Mayne, 2012; Joly, Gaunand, Colinet, Larédo, Lemarié & Matt, 2015). According to Joly et al (2015),

> *"Attribution supposes that the different causes that produce a given effect are additive, which contradicts what is observed in complex ecosystems of innovation, namely the key importance of synergistic (non-additive) interactions."*

Focusing on contribution recognises that researchers rarely work in isolation and that the realisation of impact usually requires input from many and varied actors. In this sense, contribution analysis suggests that researchers can only contribute to outcomes and impacts, they do not actually cause them (Morton, 2015). Demonstrating attribution implies that researchers must prove their responsibility and cruciality while downplaying the roles that others play, whereas demonstrating contribution can fit more easily with the collaborative approaches that are often necessary to create meaningful impact.

## 4.9: Can You Imagine?

*"The glory of research is that its immediate practical application doesn't have to be obvious…"*

- Andrew Masterson, LOLCatz, Santa and Death by Dog, 2016

Scientific discovery has always included an element of randomness and chance. Fleming's discovery of penicillin as a supposed result of experimental contamination is a classic example of research having an impact far removed from what was trying to be achieved. Others include microwave ovens, x-rays, safety glass and the pacemaker – all examples of "accidental discoveries". As Bornmann (2016) expresses it

> *"Researchers find things that they were not even looking for.*
>
> *It follows from these random elements in the process of creating knowledge that important progress in science is often unpredictable."*

The existence of high-impact outcomes arising as accidents of planned research raises an interesting question – in an environment where potential for impact has to be demonstrated in order to be funded, would the projects these researchers were actually working on have received support?

When developing new methods and technologies researchers and inventors will often have a specific use or need in mind – the original issue that they are examining. But it is not possible to predict the ways in which technologies will be used, particularly once they are released into the world, where others will mould them to suit their needs. If you are asking researchers to justify funding requests by listing potential uses and impacts, or are assessing the research too early, it is easy to overlook the largest impacts. As recognised by the National Research Council (2010), technologies can have their greatest impact when they are used in very different ways to that which was intended originally. To support this contention, the National Research Council (2010) puts forward the example of GPS (global positioning system):

> *"Originally developed by the DoD* [US Department of Defense] *to meet military requirements, GPS was quickly adopted by the civilian world even before the system was completely operational. Today, GPS is used for many applications never imagined by its creators, such as personal locators for Alzheimer's patients and pets, geocaching for treasure hunters and gamers,*

> *photo geotagging, performance measurement for sports and fitness enthusiasts, navigation systems for cell phones, and fleet management for truckers."*

As well as being another example where researchers may have very little influence on their work actually having an impact, it does raise the question of whether the originator of an idea is necessarily the best person to recognise its potential. Near the end of his life, mathematician Geoffrey Hardy (1940) wrote

> *"I have never done anything 'useful'. No discovery of mine has made, or is likely to make, directly or indirectly, for good or ill, the least difference to the amenity of the world. I have helped to train other mathematicians, but mathematicians of the same kind as myself, and their work has been, so far at any rate as I have helped them to it, as useless as my own. Judged by all practical standards, the value of my mathematical life is nil; and outside mathematics it is trivial anyhow*."

Yet Hardy's mathematical discoveries underpin the sciences of signal processing and population genetics, having major impacts outside the world of mathematics, and indeed, in wider society. As someone who was actively against the idea of his research having any use outside of mathematics, Hardy would likely be horrified at some of the uses his work has contributed to. More tellingly, in an environment where being able to identify your impact is important, would Hardy be able to secure a job and go on to make such contributions to our world?

# Chapter 5: A Question of Language

*"When I use a word", Humpty Dumpty said, in a rather scornful tone, "it means just what I choose it to mean – neither more nor less"*

- Lewis Carroll, Through the Looking Glass, 1871

Publicly funded research programs are often governed by funding contracts focused on the delivery of specified, measurable items. For large, multi-year contracts continued funding may be dependent on meeting certain deliverables on a periodic basis (for example, quarterly or annually). Reflecting the uncertain nature of research, requirements for accountability and the focus of governments on job creation, it is not uncommon for these deliverables to be in areas such as governance, employment, student numbers, paper numbers, patenting or external income generation, while research quality is assessed via peer review on a periodic basis (typically every two to five years). This allows stakeholders to hold varying views on how you determine the success of your research program. There are a number of terms utilized when discussing research impact with subtle differences that may not always be shared by all participants. Ensuring that all stakeholders are using these terms in the same way will make the assessment process easier.

## 5.1 Assessment vs Measurement

The Oxford Dictionary of English defines measurement as

> "*the action of measuring something; the size length, or amount of something, as established by measuring*" (Oxford Dictionary of English, 2005),

with the implication that measurement gives a quantifiable result , for example, the number of academic papers arising from a piece of research. Compare this with assessment:

> "*the action of assessing someone or something*" (Oxford Dictionary of English, 2005),

with assess being to

> "*evaluate or estimate the nature, ability or quality of*" (Oxford Dictionary of English, 2005).

Assessment arises from the consideration of qualitative factors and may involve the application of value judgements on measured outcomes or using the measured outcome to make a judgement. One common example of this relates to the perennial student question "Is this part of the assessment?" Assignments may be marked using a simple pass/fail, letter grades or numerical scores out of a potential maximum. In all these examples a judgement is being made on how well the student understands the material based on the content of the assignment. In an exam, aspects of the student's knowledge is being measured resulting in the number questions being answered correctly. This number is then judged to be sufficient to pass or fail the exam.

Assessment and measurement can be very closely linked, but this does not mean that one is necessarily a substitute for the other. Measurement will always have a numerical value attached to it, but it will not be dependent on a previous assessment (other than assessing the necessity or value in actually taking the measure). Assessment can be heavily reliant on firstly quantifying measures, but this is not a precondition to undertake an assessment.

## 5.2 Indicators vs Measures

Like assessment and measurement, indicators and measures are two terms that are often used interchangeably, but actually have subtle differences. Misusing these terms can obscure what is actually happening within a research program or innovation ecosystem and result in mismatches in expectations.

A measure is a

> "*certain quantity or degree of something*" (Oxford Dictionary of English, 2005),

while an indicator is

> *"a thing that indicates* [shows or suggests] *the state or level of something*" (Oxford Dictionary of English, 2005).

Lazarsfeld (1958) defined an indicator as a measurable variable which represents a particular concept. In this way the indictor acts as a proxy, which is

> "*… used as a way of measuring how the reality behind the concept changes over time and/or place."* (Gingras, 2014).

Measures can also be indicators, but when attempting to assess impact, there can be issues if an indicator is taken to also be a measure. Indicators are usually associated with a single aspect of a multi-dimensional 'something' or concept. For example, size is a multi-dimensional concept that can be expressed in words such as small, medium and large - words which only truly make sense in relation to each other. Height is a single-dimensional concept that can contribute to size and which can not only be expressed in relative terms (short, tall) but also in numerical terms (metres, feet). It is a measure that is also an indicator of size, but it is not a measure of size, merely a measure of one aspect of size – knowing a tree is 35m tall indicates that it is big, but a 35m tall oak tree is big in a very different way to a 35m tall poplar tree.

Patenting data is often used as a proxy for innovation activity – the number of patents applied for or issued is an indicator of overall innovation activity, but this neglects a significant amount of innovation that is occurring outside the formal patenting system. Product and industrial process innovation is strongly represented in patenting activity, but the nature of innovation has changed significantly over the last twenty years. It was not until the 2005 edition of the Oslo Manual: Guidelines for Collecting and Interpreting Innovation Data (OECD, 2005) that the collection of data on organizational innovation was introduced. Apple is considered a highly innovative company through both the introduction of new products and new business models surrounding those products. Design innovation plays a significant part in product innovation, often occurring in tandem with technology developments. Some countries are now incorporating registered design and trademark data in the assessment of their innovation activity.

If indicators are measures of a single aspect of a multi-dimensional 'thing' this does raise the question of whether it is actually possible to measure something as multi-faceted as research impact. It is certainly possible to measure various aspects of research impact, for example, citation data, licensing income, dollars saved following implementation of a new process. But applying a single measure is a far more difficult proposition.

By way of illustrating the difficulty of measuring multi-faceted impacts, let us look at an example from the natural world – earthquakes. The magnitude of an earthquake is usually measured using variations of the Richter Scale, but while the Richter Scale can give us an indication of the likely impact, it does not tell the whole story. The impact of a scale 6 earthquake deep below the earth's surface in remote Siberia may be very different to that of a scale 6 earthquake close to the surface off the coast of Japan. Magnitude is only one characteristic that is measured and analysed – fault geometry and seismic movement, radiated energy, intensity and depth are other important indicators of the potential impact of a seismic event.

When considering the impact of an earthquake there are obvious short-term aspects that we can measure – deaths and injuries, numbers of buildings destroyed – and longer term aspects – value of insurance claims, rebuilding costs, business losses due to trade disruption, increased calls on mental health services. All of which are important and measurable impacts. To then formulate a single measure of impact which takes into account all the possible measured aspects is fraught with difficulty. Does one weight all aspects equally? Significance of impact is often in the eye of the beholder: should the destruction of the last wild breeding colony of an endangered species be given more weight than the destruction of a fully-insured multi-million dollar building? What timeframe do you use – how long before you stop including rebuilding activity? How do you combine different units of measurement? How to account for or exclude contributing factors other than the actual earthquake? The destruction of buildings will be greatly influenced by compliance with adequate design and construction regulations. How do you separate these unrelated inputs from the quake itself?

This is not to say the development of an agreed single impact measure for activities such as research is impossible, merely that it will be extremely difficult, controversial, imperfect and unlikely to provide any meaningful information that can be acted on. In the words of van Leeuwen, Visser, Moed, Nederhof and van Raan (2003)

> *"… each type of indicator reflects a particular dimension of the general concept of research performance. Consequently, the application of a single indicator may provide an incomplete picture of a unit's performance."*

Research is a complex, multi-faceted undertaking with numerous inputs, outputs and potential areas of impact. Like any complicated event, the search for a universal single measure of impact (or metric) may ultimately be meaningless. In discussing the practices of various university ranking systems based on a single numeric value, Gingras (2011) postulates that

> "*The very existence (and persistence) of such biased indicators and rankings seems to be a consequence of the unwritten rule that <u>any number beats no number.</u>*"

Gingras (2011) goes on to note that the underlying problem with these types of indicators is that when they vary it is not possible to actually determine what any change means as it could be due any number of different factors related to each of the non-related parts of the composite indicator:

> *"Combining different indicators into a single number is like transforming a multidimensional space into a zero-dimension point, thus losing nearly all the information contained on the different axes."*

The ways in which language such as assessment, measurement, indicators and measures are used does not have to get in the way of governments determining if a research funding program has been successful. By ensuring stakeholders share a common understanding of how these terms are being applied, the benefits and limitations of the assessment can be taken in to account.

## 5.3 Quality - The *World Class Research* Objective

An unspoken assumption of nearly any government funded research program is that the research being undertaken be of, or aspiring to, world class standard. Quality itself is an abstract concept so world class is the standard to which we all aspire. Assessment programs such as the United Kingdom's Research Assessment Exercise (RAE) compare groups of researchers with their international peers – the 2008 RAE used quality rankings of world-leading, internationally excellent, recognized internationally and recognized nationally (Barker 2007). These descriptors are largely based on peer recognition, yet distrust of the peer review process is one of the drivers in the search for independent numeric assessment measures and metrics.

Just what is world class research? In the words of United States Supreme Court Justice Potter Stewart (Jacobellis v Ohio, 1964)

> *"I shall not today attempt to further define the kinds of material …. But I know it when I see it".*

The esteemed Justice Stewart may have been discussing obscenity, but the sentiment may equally apply to the notion of world class research. Being able to recognise it does not actually tell us what 'world-class research' is. In the mid-1990s, the US National Research Council reportedly spent 12 months and more than USD$300,000 (A L, 1997) to define world-class research and identify characteristics and metrics that could then be used to assess the US Army Natick Research, Development and Engineering Centre 'relative to its vision of being a world-class organization' (National Research Council, 1997). In attempting to define world-class research it was decided that a world-class research organisation is one which is recognised as such by peers and competitors in regards to several key attributes (National Research Council, 1996). Furthermore, the committee reported,

> *"After considering the various characteristics that can be used for assessing excellence, we recognized that a substantial degree of judgement is involved. For example, the number of characteristics and their level of specificity are matters of judgement. We have yet to find a standard that fits all situations".* (National Research Council, 1996).

Essentially, while there are attributes that tend to be common to world class research organisations, world class research is that which is recognised by the practitioner community as being world-class. While there is generally consensus around who are the global leaders within disciplines, it does need to be noted that excellent researchers (or research organisations) will not always undertake excellent research.

In relation to the analysis of citation data for measuring research performance, Moek (2005) contends that research quality does not necessarily coincide with what researchers themselves define or decide upon as quality, even when there is a consensus. However, while research quality is not a purely social construct, nor can it be defined and measured in the same ways we undertake these activities in the hard sciences. Moek (2005) concludes that research quality <u>is</u> an objective measure, but that objectivity is conditional on referral to an historical viewpoint such that only history (or time) will show us which contributions are both valuable and enduring, and this history begins with reading and citing the publications which bring research to the scientific community. Recognised by his peers as a leader in the study of citation analysis for research evaluation, Moek does reject the citationist notion that 'quality as measured by citation analysis is what quality is' and shares the concerns expressed by those such as Woolgar (1991): that inappropriate and widespread use of citation analysis may result in a narrowly defined notion of research quality that may ultimately be detrimental to the ongoing development and practice of science and scholarly activity.

Implicit in Moek's view is a definition of quality research as that which, over time, is demonstrated to make a valued and lasting contribution to the body of knowledge. Thus identifying quality research is subject to the same critical constraint as when identifying research impacts – time frames.

It is tempting to recognize high-quality research as that which has had a large impact but this argument probably only holds when examining impact on the body of knowledge, or, the discipline impact. Particularly in the case of applied research, it is possible for an individual research outcome to have a significant economic impact with relatively little acknowledgement within the academic community. Just because research has had a large impact does that mean the research itself was necessarily of high quality? Especially in cases where the impact has been largely negative?

While the use of bibliometric and citation analysis as tools for the assessment of research impact shall be discussed in Chapter 7.1, at this point it may be useful to posit that their most valuable contribution is as a potential indicator of research quality, itself an indicator of discipline or academic impact.

# Chapter 6: From Research to Impact

*"In the realm of ideas, everything depends on enthusiasm … in the real world all rests on perseverance."*

- Attributed to Johann Wolfgang von Goethe, poet, scientist, philosopher, statesman, circa 1820

For research to have an impact beyond its discipline it must find its way into the wider world. Industry-based research is already well on the way down this path. By virtue of being resourced it has already been decided there is a business imperative that will benefit from its findings. For academic research the path is less certain.

Theoretically there are as many pathways to impact as there are pieces of research which have an impact. Analysis of the 6,679 case studies assessed as part of the UK's 2014 REF exercise identified 3,709 distinct pathways to impact (Kings College London & Digital Science, 2015). The Australian Research Council (2016) suggests the research impact pathway is a linear progression from inputs through activities, outputs and outcomes to benefits. While in one sense this is correct, it is also simplistic. Impact pathways are also likely to include numerous feedback loops and interventions by other agents on the way to achieving impact. Translation or implementation is critical for there to be any possibility of impact, and it is the area where researchers have least control.

Hughes and Kitson (2012) suggest there are four broad categories of pathways to impact for university-based research:

1. People-based interactions, for example student placement, training, network participation;

2. Problem-solving interactions, for example contract research, facility access, informal advice;

3. Commercialisation interactions, for example patenting, licensing, company creation; and

4. Community-based interactions, for example public lectures, open days.

Similar to US studies, Hughes and Kitson (2012) found that across all disciplines, commercialisation interactions were the smallest contributor to UK academics' impact activities at around half the rate of people-based and problem solving interactions.

For ICT research the pathway to impact is often via new and improved technologies driving innovation. Technology changes can support process innovation and in recent years we have seen significant changes in the ways in which we interact and go about our daily activities as a result of changes driven by the adoption of new technologies. There are myriad factors providing the environment to either encourage or discourage these types of changes.

## 6.1: The Innovation Ecosystem

The term 'innovation ecosystem' has come to the fore in recent years, yet, as noted by Gobble (2014), consensus as to the precise definition of the term is still emerging. Ecosystems are dynamic and complex. They can be open or closed with actors in the ecosystem fulfilling particular roles and niches. Academic studies of innovation systems tend to be rather focused, on the basis that

> *"Innovation ecosystems describe the network of firms, which collectively produce a holistic, integrated product system that creates value for firms as well as end users."* (Dedehayir & Seppanen, 2015),

with ecosystems largely comprised of a 'keystone' or 'platform leader' supported by niche players. In this instance, following on from Moore (1993), innovation ecosystems have a defined life-cycle, with four phases: birth, expansion, leadership (or consolidation and establishment) and finally either death or self-renewal.

Innovation ecosystems can also be studied at the sectorial level. For example, Fransman (2014) has identified four main groups of players in the ICT ecosystem:

1. Providers of ICT equipment and products (for example, manufacturers such as Samsung, Microsoft, Huawei);

2. Network operators (for example, providers such as Vodafone, France Telecom);

3. Platform, content and applications providers (for example, Google, Amazon, Facebook); and

4. Final consumers (who will often also be content providers).

These smaller innovation ecosystems are components of larger regional and/or national innovation ecosystems, although sectorial ecosystems will cross geographical boundaries. Innovation ecosystem at the regional or national level often refers to the community of companies, universities, entrepreneurs, customers, regulatory agencies and governments that contribute to a dynamic and innovation-driven economy (Gobble, 2014).

Oksanen and Hautamaki's (2014) study of the city of Jyvasklya following Nokia's withdrawal of its research and development activities led them to conclude that for innovation to flourish requires an innovation ecosystem which includes

> *"…top-level universities and research institutions, sufficient financing and a local market, a skilled labour force, specialization as well as cooperation among companies, and global networking."*

At the regional or national level, the number and disparate nature of actors involved ensures that innovation ecosystems are complex, continually changing and subject to competing pressures. While this provides a myriad of options for government intervention, the multiplicity of choices makes it harder to choose the best one. Etzkowitz and Klofsten (2005) suggest that at the regional level, innovation policy is actually a 'bottom-up' creation resulting from 'collective entrepreneurship' arising from deep collaboration between academia, business and government. In this situation, they believe the emergence of an entrepreneurial university is the key event, with the university working with government and industry to create a support structure such that over time the role of the university and government recedes as the industry actors take the lead (Etzkowitz & Klofsten, 2005).

In recent years, this 'triple-helix' model of interaction between academia, industry and government driving innovation has been challenged by the emergence of end-user driven innovation, where demand for innovation becomes a pull-factor and results in a 'quadruple-helix' model (Miller, McAdam, Moffett, Alexander & Puthusserry, 2016). The ongoing refinement of innovation models serves to underline the fact that innovation is complex and difficult for governments to influence with any certainty.

Examination of technology-focused innovation ecosystems suggests the initial stages of the ecosystem birth phase are driven by individuals, supported by institutions, and that

> *"The presence of an ecosystem leader is indispensable at this time. In the absence of a keystone organization, which brings together and connects the actors that will develop the technological innovation, the ecosystem faces the risk of disintegration already in the invention subphase."* (Dedehayir & Seppanen, 2015).

A leader with a strong belief in the innovation and access to sufficient funds is necessary to ensure the innovation safely negotiates the 'valley of death' and enters society.

### *6.1.1: The Importance of Entrepreneurial Societies*

*"The entrepreneurship capital of an economy or a society refers to the institutions, culture, and historical context that is conducive to the creation of new firms."*

- DB Audretsch, The Entrepreneurial Society, 2009

The knowledge spillover theory of innovation arose from the observation that in some industries, innovation is primarily undertaken by small firms which may not be undertaking their own R&D. That is, those that create opportunities for innovation are not necessarily those who exploit those same opportunities (Audretsch, 2009). In knowledge economies the importance of physical capital has been usurped by human capital, and particularly the ability of people and organisations to innovate and act entrepreneurially.

European studies have shown that public investment in education and R&D encourages entrepreneurship while limited access to investment capital and the presence of burdensome regulatory regimes in relation to business initiation is a discouragement (Castano-Martinez, Mendez-Picasso & Galindo-Martin, 2015). Castano-Martinez et al (2015) also report that if the community favourably regards successful entrepreneurs so that they have a higher social status, then entrepreneurial behaviour increases as others aspire to this status. Taxes of various types, including personal and business income, inheritance, gift and sales, can also all influence entrepreneurial capital (Bruce & Deskins, 2012). Crosling, Nair and Vaithilingam (2015) suggest that while the nature and quality of a country's education system is a key component in producing citizens capable of creative and innovative thinking, it must be supported by a network of societal resources. Forming a creative learning ecosystem requires the physical and electronic infrastructure to support efficient knowledge transfer, programs to develop intellectual capital and creative thinking, interactions, systems to support compliance and best practice, appropriate incentives and institutional support (Crosling et al, 2015).

Clearly, therefore, there are many areas in which governments can undertake actions to encourage an innovative and entrepreneurial culture. But they must always keep in mind that

> *"Innovation is a complex and a highly risky venture. Innovation processes are hard to control and full of surprises. There is no guarantee that public funds invested in a project will generate innovations. … In other words, a linear analysis of consequences is almost impossible (Brulin & Svensson, 2012; Bjurulf & Vedung, 2010)."* (Brulin, Svensson & Johansson, 2012).

## 6.2: Research Idealism Meets Commercial Realities

Research undertaken within industry is generally focused on commercial outcomes, be they efficiencies, new products or solving a costly problem. It tends to be highly applicable and leaning towards the development end of the R&D spectrum. Industry looks for solutions that are cost effective and confer a competitive advantage. Free from market constraints, academic researchers may be more focused on the most complete and most elegant solution. Commercial realities can mean that 'quick and dirty' solutions may trump those that have been laboured over for years.

When research leads to new products, the technical merits of the product may not be sufficient to ensure it dominates the market. Factors well outside the technological domain may be decisive. One of the best known examples of this is the video-tape format wars of the 1980s, conclusively won by JVC's *VHS* against the Sony *Betamax* format which had been first to market. While there is a widespread belief that *Betamax* was technologically superior, but *VHS* won out because it had access to the content, there is more to the story than this. Cusumano, Mylonadis and Rosenbloom (1992) largely attribute the dominance of *VHS* to two strands of a marketing and production strategy undertaken by JVC – the successful pursuit of complementary product alliances and exploitation of superior mass production and distribution capabilities. This is a situation where the decisive factors in determining the impact of each company's research into home video recording technologies lay in their management, legal, marketing, manufacturing and logistics capabilities.

Research that results in patentable technologies and methods can have its impact reduced by the adverse effects of a company's patenting strategy. 'Patent trolling' has received much attention for its potential to inhibit innovation but patent trolling may just be the logical next step on from the defensive patenting strategy used by many firms. Defensive patenting involves companies accumulating patents for use as bargaining tools and has been criticised for increasing the costs associated with innovation, particularly that which occurs incrementally (Noel & Schankerman, 2013). It has been estimated that 30% of patents held by the top-performing Japanese companies are unused and considered to be defensive, with the majority of companies believing this strategy is a necessary defence tool against competitors (Okuda & Tanaka, 2011). Torrisi, Gambardella, Giuri, Harhoff, Hoisl and Mariani (2016) estimate that up to 70% of patent applications are filed in an attempt to block the granting of other patents and just over 25% of patents are never used, due to strategic reasons. In the US, Walsh, Lee and Jung (2016) suggest almost 40% of non-utilised patents have this status because of pre-emptive strategic business reasons such as maintaining a monopoly in regards to a particular technology. Clearly there is potential for the impact of government funded research to be constrained by these types of business practices.

Patent pools are formed when competing owners combine related patents as if they belong to a single owner and are used to overcome difficulties when complementary patents with different owners are necessary for technology production. Patent pools have an important role to play in the development and implementation of technical standards, overcoming 'patent thickets' of overlapping rights and decreasing the use of patent infringement litigation as a competitive strategy (Shapiro, 2001; Lampe & Moser, 2012; WIPO, 2014). On the surface, having a patent included in a pool would appear to be one way of increasing its impact, but as reported by Lampe and Moser (2012) and the World Intellectual Property Organization (WIPO)(2014), it would appear that patent pools are just as likely to decrease innovation and stifle competition.

Clearly companies are able to use intellectual property strategies to both increase their own competitiveness and to disadvantage their competition.

For researchers already working within industry these are the parameters in which they are used to operating, but when we try to bring academic research together with industry it becomes a significant contributor to the cultural divide that must be crossed. By directing academic research to be more relevant to industry we run the risk of creating a situation where researchers focus on finding problems for solutions they have developed rather than solutions for actual problems.

## 6.3: Politics, Polling and Policy

*"The task of innovation policy is to ensure that the nation has a coherent, well-managed, and well-funded set of private and public institutions that can function well as an NIS* [National Innovation System]"

– Christopher T Hill, The Post-Scientific Society, 2007

In the hands of government, research outcomes can be an extremely powerful tool, with the potential to change the lives of many through the implementation of recommendations from findings as policy or practice. Public health is one area where many research outcomes inform policy and practice, for example, vaccination programs, cigarette advertising restrictions, screening programs and pharmaceutical subsidies. But realising these impacts can be subject to the vagaries of political considerations. Even where research has been specifically commissioned by government the findings and recommendations may not be implemented if the political stars do not align.

The development and implementation of any government policy is driven by more than just being 'fit for purpose' as determined by supporting research. Public opinion (and its effect on voting intentions), vested interests and their lobby groups, economic costs, opportunity costs, competing priorities and ideology all play a part in decision making at the political level. As noted by Oliver, Innvar, Lorenc, Woodman and Thomas (2014), the decision making context and other influences have as much influence in determining policy as any research evidence. While it is not uncommon to hear politicians of all persuasions talk about the need for evidence-based decision making, the reality is that any reliance on evidence can be very selective.

The relationship between research and public policy has perhaps been studied most in the fields of medicine and public health. In 1994, Walt suggested that barriers to influencing policy include political, conceptual confusion/scientific uncertainty, timing and communication and posited that

> "*To influence policy we need a distinctive awareness of power and other political realities constraining the process of policy development and implementation … by using a policy analysis framework it is possible to identify and overcome the barriers to research influencing policy.*"

Walt (1994) also suggests that perceptions, understanding and acceptance of risk may also be important, and this problem is often exacerbated by media reporting. Many of us are quite familiar with newspaper headlines proclaiming that a particular activity will double your risk of dying from a certain disease, while the fact that your original chance was only one in ten million is buried deep in the article, where many readers never get to.

The ability of health intervention research in Australia to impact on policy and/or practice is considered to be influenced by a number of factors including the presence or absence of statistically significant intervention effects, the researchers experience and connections, dissemination and translation efforts and the post-research context (Newson, King, Rychetnik, Bauman, Redman, Milat, Schroeder, Cohen & Chapman, 2015). Earlier research on the ways in which Australian policy makers utilise the expertise and findings of public health researchers found that contextually responsive research expertise is valued, where formulators of policy who are engaged with research are able to also utilise the researchers for related activities such as clarifying ideas, giving advice, persuading politicians and the public and defending the resulting policies (Haynes, Gillespie, Derrick, Hall, Redman, Chapman & Sturk, 2011).

One would expect that when seeking information and advice to inform policy, accessibility and (perceived) relevance will be key determinants as to whom advice is sought from. A study of various Commonwealth and State government bodies in Australia found that being able to easily access and having a high level of association with the entity or individual who is providing information is an important factor in determining what value public officials will allocate to various sources of information (Cherney, Head, Povey, Ferguson & Boreham, 2015). Given this, it should not be surprising that while academic researchers are considered relatively important sources of information they are not consulted as often nor considered as important as staff within the same or other government agencies. The main reasons for this have been articulated as insufficient time to engage with the academic literature and limited opportunities to develop relationships and linkages with researchers (Cherney et al, 2015; Head, 2015). Difficulties associated with being able to form linkages with researchers are of particular concern, given that most policy makers use informal networks to identify those to be consulted (Haynes et al, 2012). Visibility via media profiles also helps policy makers identify researchers, and may also help to confer credibility although not all media appear to be equal. Ouimet, Bedard, Leon and Dagenais (2014) found that while radio, newspaper and weekly magazine activities are associated with researchers providing greater briefings to policy makers, the reverse was the case for those who appeared on television.

Personal relationships are built on trust, mutual understanding and honesty. If, as noted above, policy makers lament the lack of opportunities to develop relationships, then researchers attempting to work in particular policy areas are frustrated by frequent changes of personnel also making that relationship building difficult (Kothari, MacLean & Edwards, 2009). The importance of personal relationships can be seen in Innvaer, Vist, Trommald and Oxman's (2002) review finding that lack of personal contact and mutual mistrust were the most common barriers to the use of evidence-based research findings in policy formation. Additionally, they posit that

> *"Personal two-way communication may also be a necessary precondition for other facilitators. For example, without personal two-way communications it may be difficult for researchers to understand what decision-makers regard as timely, relevant or good quality research."* (Innvaer et al, 2002).

If researchers are able to develop good relationships with policy makers this provides a valuable avenue for their work to inform policy development. But this does not guarantee policy will be adopted.

### *6.3.1: Left Hand, Right Hand and the Law of Unintended Consequences*

The undertaking of research and the implementation of its findings in society typically operates across a number of governmental portfolios in various jurisdictions - science, education, industry, health, environment, agriculture – all the while never being the core focus of any single portfolio. Within Australia, for example, publicly funded agricultural research happens under the auspices of a number of State and Commonwealth departments including:

- the Commonwealth Department of Agriculture, via the rural research and development corporations;
- the Commonwealth Department of Industry and Science, via the Commonwealth Scientific and Industrial Research Organisation (CSIRO);
- universities, via the Commonwealth Department of Education and Training;
- various state Departments such as Primary Industries, Resources, Economic Development.

In 2011, the Rural Research and Development Council produced a *National Strategic Rural Research and Development Investment Plan* with fourteen recommendations including

*"Recommendation 14: The Australian Government should ensure adequate provision for the maintenance and implementation of the Plan by endorsing a key advisory body to guide more effective multi- sector cooperation and the prioritisation of Australian Government investment in RD&E for Australia's rural industries."*

In putting forward this recommendation the Council notes that:

> *"Given the complexity of the rural RD&E system, many of the Plan's recommendations go beyond the direct influence of one minister and can only be addressed through collaboration with other Australian Government ministers and departments, state governments and the business sector.*
>
> *The Council believes that system-wide leadership is required to provide focus and to help position rural RD&E investment within the broader national and international innovation system. Notwithstanding the importance of the business sector, a whole-of-government approach is required given the number of portfolios with an interest in rural RD&E."* (Rural Research and Development Council, 2011).

When any multi-faceted activity is located across multiple portfolios there is always the possibility of competing policies and actions. Policy directives from one government portfolio may have undesirable flow-on effects hampering desired policy outcomes in another portfolio. An example of this can be found in how the traditional funding and reward systems governing research undertaken in Australian universities may have stifled activities which promote research impact.

Most research undertaken within Australian universities is funded from outside the university itself, and universities then receive Commonwealth funding in the form of research block grants, based on input and output metrics relating to this research[13]. For many years, metrics contributing to the value of these grants

[13] https://education.gov.au/research-block-grants-calculation-methodology, accessed 6th June 2015

have included research income, research publications, research higher degree student load and completions, and research staff. Research income has been allocated to one of four categories depending on the source:

1. Australian competitive grants – this includes funds received from the main research funding bodies, the ARC and the NHMRC;

2. Other public sector – commonwealth, state and local government funding which does not meet the criteria for competitive grants including contract research;

3. Industry and other – this includes contract research undertaken for industry, international grants and many philanthropic grants;

4. Co-operative research centres – funding received by universities for work undertaken as part of their involvement with research centres established under the Commonwealth co-operative research centre program.

It is recognised that the funds provided to universities under Australia's main research grant programs do not fully cover the cost of undertaking the research and training doctoral students. The federally funded *Research Block Grants* are a series of mechanisms to alleviate this shortfall. However, when calculating the value of a university's Research Block Grant, income from Australian competitive grants has traditionally been the category that matters most. Research publications such as books, journal articles and conference papers have counted towards calculating the Research Block Grant value, but not patents (Watt, 2015).

There is no government funding mechanism which rewards universities directly for many of the engagement activities that encourage research impact: industry-university staff exchanges, public seminars, university-industry workshops. In terms of indirect financial return via the research block grants, industry-derived funds have thus far played a smaller role than competitive grant funds. In a stark choice between a dollar of industry funding or a dollar of competitive grant funding, universities were financially worse off if they chose the industry funding. Particularly for those universities successful in obtaining competitive grant funding, there was no incentive to pursue industry collaborations at the expense of competitive grants. In Australia, many of the smaller universities which have grown out of the technical colleges are far better at engaging with industry than the large established 'Sandstone' universities. This is a matter of necessity for them – unable to break the stranglehold the established universities have on competitive grant funding they have no option other than to look to industry to support their research activities and yet, the rewards from government for this engagement was less.

Wherever universities are rewarded for their activities, so too will they reward their staff.

If universities are preferentially rewarded for focusing on research income that is limited to specific government programs and for producing research outputs that are measured by their influence on the academy, then it should be no surprise that the reward mechanisms for their staff are also biased in this direction. Traditionally, appointment and promotion of academic staff has been dominated by grant and publication performance with limited incentives to undertake other activities which may help disseminate research outcomes in society. As noted by Wardale and Lord (2016) in relation to industry collaboration, if the reward systems in universities do not recognise various types of interactions with industry then they are likely to be seen as being of lesser value than the traditional academic research approaches.

Given Australia's low levels of university-industry collaboration compared to other members of the OECD, a lot of thinking and policy development has been occurring in recent years as to how to improve the situation. Many initiatives in this area are driven by the Department of Industry and Science, such as the long-running co-operative research centre program. But as has been noted by PriceWaterhouseCoopers (2015), the original Research Block Grant funding mechanisms are biased towards research excellence and should be re-oriented to

> *"… create a better balance between academic excellence and industry engagement – and realising that good commercial outcomes arise from quality research…"*

such that increased incentives are provided for industry-university collaboration. This will then influence appointment and promotion criteria in universities and academics will respond to these incentives.

In 2015, as part of the *National Innovation and Science Agenda* (Commonwealth of Australia, 2015), the Australian Government announced that the Research Block Grant scheme would be revised in 2016 to encourage and reward industry engagement. Until this funding policy that currently meets the needs of the Department of Education and Training is re-aligned, the success of policies implemented by the Department of Industry and Science to increase industry-university collaboration will be limited. This change may be a step in the right direction. Implementing the recommendations of the Watt Review of Research Policy and Funding Arrangements (Watt, 2015), the Australian Government intends to simplify the Research Block Grants such that six schemes are combined into two: a research support scheme and a research training scheme.

Under this new mechanism, research support would be based on equal weighting of competitive grant and other research income received, with research outputs such as publications no longer having any effect (Watt, 2015). While this has largely been welcomed, concerns have been raised that the removal of research outputs as a factor in determining grant value may disadvantage the humanities, arts and social sciences, where Australian businesses are explicitly excluded from claiming research and development taxation concessions (Turner, 2016; McColl, 2015). This would be unfortunate, given the contribution that that the humanities, arts and social sciences make to furthering our understanding of the world we live in and in realising the potential of new technologies. The creative arts and technology are intimately linked in rapidly growing industries such as computer gaming. The social sciences provide important insights into how people will respond to technology and contribute to successful implementations across society. It has even been suggested that innovation and continued economic success may actually come to rely more on factors other than science and technology advantages:

> *"There are growing indications that new innovation-based wealth in the United States is arising from something other than organized research in science and engineering. … not as much by mastering the intricacies of physics, chemistry, or molecular biology as by structuring human work and organizational practices in radical ways."* (Hill, 2007).

Given the myriad factors affecting industry's propensity and ability to directly engage with university research, it will be interesting to observe how these changes affect collaboration rates. It will take time for these changed sector-level incentives to be reflected in the incentives offered to individuals at appointment and promotion. This represents a major incentive change for one side of the university-industry relationship that must be matched by incentives for the other.

The previous ranking of industry income as being less worthy of reward under the Research Block Grant scheme is one instance where two arms of government have unintentionally compromised each other's policy aims. It would not be surprising to find others. As noted in the 2008 review of Australia's innovation system,

> *"There is a lack of policy coherence reflected in a fragmentation of innovation resources across government and between state, territory and federal governments. There is a focus on the short term in resource allocation."* (Cutler & Co, 2008).

By necessity this new framework must cross ministerial and jurisdictional boundaries, covering a broad range of policy areas and be focused on co-ordination, without developing into a centralised function of government (Cutler & Co, 2008).

Having policies which align across all departments and levels of government would be expected to promote the achievement of research impact and ensure that a nation receives the optimal return on their investment.

### 6.4: How Much Influence Do Researchers Really Have on Realising Impact?

In some ways the recent trend towards assessment impact for research has appeared to be based on the assumption that research traditionally has not been concerned with impact. While the pursuit of knowledge for its own sake is likely at the forefront of researchers minds when considering why they pursue a given research question, there are very few that would admit to not wanting their research to have an impact in some way – from providing insights to the human condition to curing a deadly disease. At the very least, the peer recognition mechanisms that academia has developed over the last 150 years are largely based on discipline and teaching impact.

When using impact for allocation of research funds, once issues surrounding time frames and attribution have been resolved, one then has to consider if impact-based funding is then rewarding (or punishing) researchers for activities that are largely out of their control. As noted by Morton (2012),

> *"Any assessment of impact from social research needs to acknowledge that many actors are involved in the process of research being taken up and used, and impact cannot be achieved from the supply side alone."*

Similarly, Buxton (2011) notes that while most researchers do want their researcher to have a positive impact, many are just as concerned that both they and their research will not only be judged, but also rewarded, based on this impact which they have limited influence over.

In Australia, 26.6% of research and development expenditure is made by members of the higher education sector, almost twice the rate of that in the USA (OECD, 2014). This is the academic sector, with traditions of teaching and learning and the pursuit of knowledge for its own sake. Here is not the place to address philosophical questions regarding the role of the university in the modern world, but it has to be noted that traditionally the mechanism by which universities have impacted on wider society has been through the diffusion of their graduates.

Moving towards a more direct research impact poses significant challenges for universities as ways of achieving this tend to be outside of their traditional core business. This means researchers are heavily reliant on others, often outside of their sphere of influence, to implement their findings.

De Jong, Barker, Cox, Sveinsdottir and Van den Besselaar (2014) cite the example of a Dutch ICT project which developed improved methods for analysing the consistency of medical protocols. While successfully demonstrating the methods applied to the treatment of breast cancer and undertaking the project in collaboration with an institute charged with improving health care quality, the new methods had not been implemented to date. The reason for this is cited as a lack of absorptive capacity within the medical sector and the need for significant change in current practice and culture. This does not mean the work will not have any indirect impacts, nor that it will not be implemented in full at some time in the future. By virtue of showing that things can be done better it may promote changes in other areas. But this is clearly an instance where the researchers are very limited in their ability to influence how their work may have impact at the present time.

When discussing why ICT pilots and projects persist in large numbers in areas like e-health and telemedicine, Andreassen, Kjekshus and Tjora (2015) conclude that culture and social conditions (which are partly created by the use of projects themselves) are important factors promoting the continued use of pilots rather than large-scale implementation. They suggest the continuing use of pilots and small projects may be partly due to the tensions between state regulation, medical professional autonomy and ICT innovation. An example of these tensions can be found in the recognition that staff need to be enthusiastic and committed to implementation, but that there can be challenges in generating and maintaining this commitment when the health-care system is focused on productivity and performance indicators (Andreassen, Kjekshus & Tjora, 2015).

At a workshop specifically focused on the question of whether it was possible, and if so how, to measure the impacts on and benefits to society of US federally-funded research it was noted that

> *"… impacts typically depend on complementary actions by entities other than the federal government. This is particularly the case as fundamental research moves toward technological innovation, implementation and practice."* (Olsen & Merrill, 2011).

Durlak and Dupre's (2008) review of more than 500 studies concluded there were at least twenty-three contextual factors influencing the implementation of programs, which they then grouped into five main categories:

- Community level factors (for example: politics, funding, policy);
- Provider characteristics (for example: perceived need and benefit, proficiency);
- Innovation characteristics (for example: compatibility, adaptability);
- Organisational capacity (for example: organisational norms, leadership, communication); and
- Support systems (for example: training, technical assistance).

From the point of view of researchers attempting to have their findings implemented, whether through new practices, policies or products, it is obvious the opportunities for them to intervene in pursuit of increased impact are limited. Within the academic sphere, much research work is self-directed. The researcher selects the problem to be worked on, based on a variety of personal motivations. When researchers work on externally directed research, whether as part of a research contract or their employment by the research arm of a company, the work is undertaken and the results handed over for others to make decisions about how that research is used. Rarely are researchers themselves part of that decision making group.

It has been suggested that in the Australian context, innovation and knowledge transfer between universities and industry suffers from a demand shortage rather than one of supply. Many Australians can quote the black box flight recorder as an example of an innovation that failed to receive support locally and hence the economic benefits were largely realised elsewhere. Collier, Gray and Ahn (2011) quote a senior American university technical transfer office manager as saying

> *"The limitation on technology transfer from Australian universities was not [with] the universities [because], I thought, by and large the offices of technology transfer seem to know how to do it, but it was on the receptor side that the availability of early-stage risk capital was limiting, and the availability of experienced management who knew how to do start-ups."*

In 2016, Australia ranked third in the *Global Entrepreneurship and Development Institute* (GEDI) Index Rankings, behind the USA and Canada[14]. The social and economic infrastructure within Australia, along with our abilities, attitudes and aspirations combine to provide supportive conditions for entrepreneurship to arise. Studies also show that Australia is middle-ranking when it comes to management performance (Bloom & Van Reenen, 2007) and ranks particularly poorly in regard to 'instilling a talent mindset' whereby senior managers are evaluated and held accountable based on the strength of the talent pool they are actively involved in building (World Management Survey, 2009). Also of concern in the Australian context is Jackson's (2014) contention that personality traits exhibited by Australian business graduates suggests

> *"Although they demonstrate some of the required qualities for leadership emergence and transformational leadership, they may favour conventionalism, … Similarly, business graduates may not initiate and manage the innovative processes at the rate needed for Australia to remain globally competitive."*

[14] https://thegedi.org/global-entrepreneurship-and-development-index/, accessed 4th May 2016

In addition, collaboration between industry and both universities and government is poor (Dodgson, Hughes, Foster & Metcalf, 2011). Cuthill, O'Shea, Wilson and Viljoen (2014) suggest the lack of a clearly articulated national policy in relation to knowledge exchange is reflected in poor project management and collaboration skills, along with limited motivation, in universities. Dodgson (2015) characterises this deficit in industry-university collaboration as resulting in a situation where Australia is relatively good at initiating companies but quite poor at growing them to become larger companies and suggests that Australia's innovation system is hollow in the centre due to a lack of proper connections between the various institutions supporting innovation activities. This accords with Bloch and Bhattacharya's (2016) assertion that with high entry and exit rates, Australian SMEs can experience rapid growth and profitability in their early years, but decline over time, as does their innovation activity. Dodgson et al (2011) suggest that when it comes to formulating innovation policy a major shift is required, replacing a 'market failure' approach with one that is focused on 'systems analysis'.

If innovation in Australia truly does suffer from a lack of demand, whether due to management failures, risk aversion, capital scarcity or a dysfunctional innovation system, then how do we justify focusing on the supply side, via impact assessments, as a way to address the problem?

## 6.5: Is Potential for Impact a More Realistic Assessment?

*"Free the child's potential, and you will transform him into the world"*

- Maria Montessori, Educator, The Discovery of the Child, 1966

In their analysis of 2010 UK Research Excellence Framework (REF) case studies Khazragui and Hudson (2015) found that

> *"…at some stage all research needs the involvement of others to convert it into impact. Hence, research may not subsequently have a substantial impact because of the lack of involvement of suitable impact partners."*

Given that researchers, and usually their institutions, have so little control over whether their research really does have an impact on wider society, it may be better to focus assessment on the potential for impact, particularly when it may take decades for the impact to be fully realised. As noted by the National Research Council (2012), by the time that happens there may have been so many other actors involved in bringing the impact to fruition that the original link with the researchers may have been lost.

Assessing potential for impact can be done at two levels:

1. How can the individual piece of research be useful to society: and
2. What are the barriers to that research being used and how can they be overcome?

Identifying the potential impact for an individual piece of work requires the researcher to place their research question in context: How does it fit within related work being done locally or internationally? Is it directly addressing a recognised problem? Who might benefit from the research? For researchers working at the applied end of the spectrum these questions are relatively easy, but for those undertaking blue sky research the answers are probably not obvious.

Medical research is an area where impact can be relatively easy to identify and quantify – new treatments, changes in clinical guidelines and changes in health policy can lead to improvements in morbidity rates or decreases in risk-taking behaviour. Yet the way in which case studies are presented may be mis-representing the actual impact. Greenhalgh and Fahy (2015) found that for 162 health sciences case studies submitted as part of the 2014 UK Research Excellence Framework, the majority cited shorter-term changes in policy, guidelines and practice as the main impact, with relatively low emphasis on improved patient outcomes. They suggest there is a

*"… mismatch between the sophistication of theoretical approaches to assessing impact published in the specialist 'research on research' literature … and the direct and linear way in which the research-impact link was actually depicted and scored in REF2014 submissions".* (Greenhalgh & Fahy, 2015).

While recognising that the REF template may have encouraged this approach, they do make the point that collaborative and co-produced research is generally not linear and there may be conflict or power issues in these relationships that will affect the achievement of meaningful impacts.

The *Social Impact Assessment Methods through Productive Interactions* (SIAMPI) framework developed by Spaapen et al (2011) examines the interactions between researchers and various stakeholders in order to study the mechanisms by which research impacts on wider society and how those impacts may be assessed. Penfield, Baker, Scoble and Wykes (2014) note that SIAMPI is not intended for use as an assessment tool where the value of a piece of research is judged, but rather, functions best as a learning tool, which can provide new insights in to how these interactions lead to societal impact. Nevertheless, SIAMPI may provide a way to indicate potential for impact, even if the correlations and causations are still unclear.

SIAMPI identifies three types of *productive interactions* which can lead to potential for social impact:

1. *Direct* interactions – these are those which occur between two or more people and may include meetings, phone calls, or email correspondence.

2. *Indirect* interactions – these are those which occur via an intermediary, non-human, carrier of the information and may include research papers, practice guidelines, exhibitions, models, or film.

3. *Financial* interactions – these are those where there is an economic exchange between researchers and stakeholders and

may include activities such as research contracts, licencing fees and inkind contributions to research. (Spaapen & van Drooge, 2011).

From the SIAMPI framework we can infer that one way to assess the potential for research impact at an institutional level is by examining how easy it is for the community to interact with researchers in the institution and how often they do so. Indeed, the Australian Academy of Technological Sciences and Engineering has suggested that the already tracked metric of non-competitive grant research and commercialisation income be used as a proxy indicator metric for this ease of access (ATSE, 2014).

Metrics such as contract research and licencing income are attractive indicators in that they are likely to have an association with both the usefulness that industry perceives a given thread of research has and of the ease with which they can interact with the organisation. They are also easy to capture within existing financial reporting systems. As always however, caution must be exercised when relying on these measures as proxies for engagement with industry and impact.

While there have been a small number of successful patents and licences generating significant amounts of revenue for their universities, in 2007 only 13 US universities had earned more than USD$25 million from patents and licencing, with the median licencing revenue at $1.8 million (Popp Berman, 2012). Of the USD$1.39 billion earned from licencing revenue by US universities in 2004, one fifth went to only two universities, with eight receiving more than half of that year's revenue (Haupt, 2006). In 2013/14, UK universities received £75 million in licensing revenue, one fifteenth the value of that earned from contract research (HEFCE, 2015b). Haupt (2006) also notes that engineering patents are generally of low value, with the big revenue tending to be associated with pharmaceuticals. Harhoff, Henkel and von Hippel (2003) include chemicals and chemical processes as the only other places where large licencing incomes can be typically found while noting that previous studies point towards low returns from the licensing of patented knowledge as being the norm. A single piece of IT hardware may incorporate a hundred different patents, so that the value of a single patent is quite small (Grose, 2006). This accords with the findings of the major post-war US defence research analysis, *Project Hindsight*, that

> *"… large changes in the performance/cost are the synergistic effect of many innovations, most of them quite modest."* (Chalmers & Isenson, 1967),

a situation that appears to still be quite common. Thus, small amounts of income earned from licensing and patents may obscure the numbers which are actually being granted to industry to use and the contribution of each to the final result. In addition, as noted in Chapter 6.2, companies can seek patents and licences to stifle competition rather than generate new income.

In light of this uneven revenue distribution and low value for individual engineering and IT patents, Fisch, Tobias, Hassel, Sandner and Block's (2015) finding that higher patenting numbers are associated with a university's technological focus on chemistry, electrical engineering and mechanical engineering suggests that for many universities it is possible their investment in intellectual property protection far outweighs any returns they may receive.

In many developed economies university academics are able to undertake activities such as consulting independent of their employer, often utilising up to 20% of their time, and may even pursue their own commercialisation activities outside of the institution (Amara, Landry & Halilem, 2013). These activities are situated between engagement and university licencing, patenting and research contracts in terms of formal recognition and reporting and may not be easily recorded by universities. In their study of Imperial College, Perkmann, Fini, Ross, Salter, Silvestri and Tartari (2015) estimate that almost one third of patenting activity, three quarters of consulting activity and nine tenths of company establishment by academics occurs outside of the College's support structures. Relatively high levels of outside entrepreneurship have also been found in the USA (Fini, Lacetera & Shane, 2010; Thursby, Fuller & Thursby, 2009). Amara, Landry and Halilem's (2013) study of Canadian engineering and natural sciences academics found that more than half had been involved in un-remunerated consulting. Relying on industry-sourced income received by universities may therefore significantly underestimate the involvement of researchers in business development and service activities, and hence their resultant impact.

Making it easy for society to access the outputs from research undertaken by publicly funded organisations has become a political imperative in recent years. This has resulted in policies such as those implemented for US National Institutes of Health grants, requiring the deposit of resultant publications in the *PubMed Central* database (US Department of Health & Human Services, 2014). While these policies are occasionally threatened by attempts to legislate against them (for example, the proposed 2011 Research Works and 2008 Fair Copyright in Research Works Acts, both in the USA) the trend is increasingly towards making the primary output from publicly funded research freely available to the public via open access repositories. But this is only part of the story. Industry relevant research must be supported by intellectual property and contractual policies and procedures that support the transfer and exploitation of knowledge, not impede it.

Open access to research outputs via the literature increases the potential impact of an individual piece of research by making it more easily accessible in one sense, but how realistic is it to think that this will increase impact outside the academy? Given the way that research papers are often written, full of highly technical language, there are relatively few members of the public not intimately involved in the field who will be able to take advantage of the information revealed. The rise of open access literature and policies directing this does have great benefit in terms of democratising access to cutting edge research, but the beneficiaries of this tend to be those for whom such access results in decreased operating costs such as universities, publicly funded research organisations, government departments, and not-for-profits, especially in developing countries. While industry may also benefit from this access to the literature, researchers working in the space are adept at balancing publication with intellectual property protection so that information in the paper is of limited value. Companies may also be more interested in breakthroughs that are protected so they can acquire exclusive exploitation rights. This means that while open access may accelerate research progress by removing financial barriers to information, it may not necessarily have a discernible increase on wider impact.

Other barriers to impact tend to operate at the institutional level or above. Policies regarding intellectual property transfer are set by the organisation or may be influenced by funding body or government requirements. In environments where government funding for research is stagnating or decreasing, universities look to the intellectual property developed by their academics as an alternative income stream. As discussed earlier in this chapter, this may be unrealistic, but nonetheless intellectual property issues can contribute to university-industry contract negotiations taking months or even years. A common charge from industry is that universities overestimate the value of a piece of intellectual property and underestimate the investment that will be required to take the property to market. Universities will counter that industry is unwilling to pay for the full cost of research – the long-term investment in laboratories, equipment and staff that allows the intellectual property to be developed. Many universities start from a uniform approach to intellectual property regardless of the client – to retain ownership and provide first rights on exclusive licencing. Yet the industry approach to, and usefulness of, intellectual property rights may depend on the sector (Sterckx, 2011). Grose (2006) asserts that IT companies prefer non-exclusive licenses or all intellectual property to go in to the public domain, while aerospace and bioengineering prefer to own any arising property. This aligns with Bessen and Meurer's (2008) suggestion that patenting of software is largely opposed by those within the industry itself and that patenting itself may be detrimental for the industry. Clearly, flexible intellectual property policies are conducive to government funded research having impact via industry.

Compared to other OECD countries, Australia has a relatively low level of research interaction between universities and industry. There are a number of factors which contribute to this, one of which is the difficulty that industry can experience in knowing exactly where in the academy the expertise they need resides.

Traditionally universities are structured according to teaching disciplines and while this means that academics within a particular department share a core of expertise, the research strengths can be very diverse. Individuals also vary greatly in their ability to accommodate commercial realities in their approach to research. The cultures of academia and industry can be very different and on both sides there will always be some individuals for whom working with the other is very difficult and may be counter-productive.

Successful long-term research relationships are built on personal relationships, trust and an understanding of each side's imperatives. Schofield's (2013) finding that

> *"Most respondents agreed that mutual trust and cultural empathy are critical success factors in developing international research partnerships."*

applies to all university-industry collaborations in the sense that empathy and understanding regarding the differing cultures of industry and academia is key.

Doctoral holders who work in industry are very important in this regard, providing valuable links. Increasingly, universities are also using dedicated staff and units to support industry-university interactions, acting as one-stop shop fronts.

### *6.5.1 Case Study – The Defence Science Institute (DSI): A Collaborative Regional Approach to Sectorial University-Industry Engagement*

Academic motives for engaging with industry are as a varied as academics themselves, but in the engineering and physical sciences it is possible that motives associated with furthering the research agenda are more influential drivers than those associated with commercialising research (D'Este & Perkmann, 2011; Franco & Haase, 2015). These include motives such as accessing equipment, data and expertise, learning from industry, testing research against industrial problems and securing funding to cross-subsidise other research activities. Universities have created technology transfer offices to facilitate activities such as consulting, patenting and licencing as they search for new income streams. But for individual academics, these may be a less attractive form of industry interaction:

> *"… the more commercial forms of interaction are rarely* ***directly*** *conducive to carrying out academic research. For instance, data derived from consultancy work or contract research may not be sufficiently novel for publication. However, these direct effects tend to be outweighed by indirect benefits such as learning and access to research funding. Learning is an indirect benefit in that industry projects may not lead directly to novel scientific outputs, but may lead to new research problems…. Access to funding is also an indirect benefit as it may facilitate economies of scale and retention of staff at university laboratories."* (D'Este & Perkmann, 2011)

Laine, Leino and Pulkinnen (2015) suggest that for Finnish academics, improving graduate employability, improving student learning, improving their own research reputation, accessing research funds and contributing to improving business performance rank as the main benefits of working with industry. Clearly, there will often be more than one reason for why an academic researcher decides to pursue a relationship with an industry partner.

Industry motives for engaging in collaborative research tend to focus on practical outcomes that will lead to competitive advantage and improved financial performance - solutions to identified problems, staying abreast of the latest technological developments – but there can also be an altruistic component (Berman, 2008; Ankrah, Burgess, Grimshaw & Shaw, 2013). Companies can also value the opportunity to identify and begin building relationships with potential employees (Broström, 2012; Ankrah et al, 2013).

Regardless of the motives for wanting to engage, the challenges for both academic and industry players are significant. In regards to collaborative research projects, Sandberg, Pareti and Arts (2011) neatly summarise the issue as

> *"… industry and academia have different objectives (new products and sales versus new knowledge and fundraising) that complicate CPR* [collaborative practice research] *management. Although it's relatively easy to agree on challenges and goals, viewpoints differ regarding variables such as relevance, rigor, time horizons, planning practices and predictability."*

Meanwhile, Collier, Gray and Ahn (2011) quote an industry partner as saying

> *"Academics are at universities because they are interested in technical issues or in what particular [interests them], not in being commercial; trying to expect them to be both is silly."*

These points of difficulty reflect some of the cultural differences between academic and industry research, which underlie many of the barriers to university-industry collaboration (Bruneel, D'Este & Salter, 2010; Partha & David, 1994), although according to Hughes and Kitson (2012), cultural differences and intellectual property issues are not considered to be the main barriers by academics themselves. In addition, there are often structural difficulties such as time consuming bureaucratic practices and a lack of organisational support for academics attempting to work outside the traditional teaching and research frameworks (Franco & Haase, 2015; Berman, 2008). United Kingdom studies suggest that a lack of time, university bureaucracy, insufficient rewards for the effort and inadequate support are considered by academics the main impediments to working with industry (Hughes & Kitson, 2012; Watson, Hall & Tazzyman, 2016). Wardale and Lord (2016) express the challenge as being able to use knowledge and experience that has been gained from working with industry within organisational frameworks which may say they are entrepreneurial, yet appear to do little to encourage this type of behaviour in individuals. Indeed, from personal experience, Wardale and Lord (2016)

> *"… found many policies and procedures have had the effect of hindering, rather than enabling, an entrepreneurial approach…"* (Wardale & Lord, 2016).

Any barriers to research and development collaboration are magnified for small-to-medium enterprises (SMEs). Even when they wish to engage with universities and public research institutions, many SMEs do not have the resources to do so. A particular issue for SMEs is having suitably qualified personnel who also possess the management skills necessary to successfully undertake collaborative research projects or to exploit the results. That is, they lack absorptive capacity at the company level, as sometimes evidenced by a lack of internal R&D activity (Jung & Andrew, 2014; Laine, Leino & Pulkinnen, 2015; Bucar & Rojec, 2015). For those companies which do have internal R&D activities, it may be that the direction in which this is focused might also play a part in their absorptive capacity. Soh and Subramanian (2014) suggest that companies with R&D programs focused on original knowledge production do not gain as much benefit from collaboration with universities compared to those with R&D programs focused on the recombination and extension of existing knowledge into commercially-oriented outcomes. Intuitively this makes sense – university researchers tend to be focused on the production of original knowledge so collaboration with similarly focused companies will not necessarily bring anything new to the company.

A similar problem for industry in relation to having staff with suitable absorptive capacity is faced by universities who want to recruit staff with industry or entrepreneurial experience in addition to rigorous academic qualifications – the pool of potential staff is relatively small. It has been suggested that a perceived lack of employment security associated with SMEs puts them at a disadvantage when recruiting highly skilled staff (Sohn & Kenney, 2007). However, Moy and Lee's (2002) study in Hong Kong found that SMEs there actually offer a higher percentage of permanent employment contracts and greater opportunities for rapid career progression than multi-national corporations. One could also suggest that within the IT sector, the experience and culture of companies such as Google, Facebook and EA Games has greatly improved the appeal of start-up companies as employers of choice, so this disadvantage may be lessening.

Small to medium enterprises are a significant part of the Australian economy, and the bulk of these are unincorporated businesses owned and operated from within the household sector - effectively sole traders and family enterprises (Australian Bureau of Statistics, 2015a). While SME's make up an estimated 97% of businesses and are responsible for 49% of private sector employment (Bhattacharya, 2014), 61% have no employees and a further 27% have less than five (Australian Bureau of Statistics, 2015a). Around 3% of new enterprises with less than ten employees exhibit significant growth in their first five years and these account for more than three quarters of the job creation by enterprises in this category (Bloch & Bhattacharya, 2016). Similarly, in the United Kingdom, SMEs make up 99.9% of private sector business and are responsible for 60% of private sector employment, but 76% have no employees and 99.3% of the UK's private businesses have between 0 and 49 employees (Department for Business Innovation and Skills, 2015). In the United States, 98% of companies have fewer than 100 employees and contribute 34% of jobs, with 63% of these smaller companies having four or less employees (United States Census Bureau, 2012).

Governments at both the Commonwealth and State level in Australia are keen to see an increase in the level of engagement between universities and SMEs, but given the dominance of 'micro' enterprises it would seem that even for those that are keen, issues of resource and time availability are likely to be acute.

Interestingly, Australian enterprises with less than five employees are more likely to engage in collaborative research and development activities than their slightly larger counterparts (Table 3). Closer investigation of this phenomenon is warranted, but the extent to which this higher level of collaborative R&D is linked to technology-based spinouts or consulting and contractor activities is not examined here. Suffice to say, start-ups which maintain research alliances with universities may experience greater employment growth, provided they have sufficient scientific absorptive capacity to be able to adequately exploit the relationship (Toole, Czarnitzki & Rammer, 2015).

| Collaborative arrangements, by employment size, 2013-14 | | | | | |
|---|---|---|---|---|---|
| | 0-4 persons | 5-19 persons | 20-199 persons | 200 or more persons | Total |
| | % | % | % | % | % |
| Joint research and development | 2.7 | 1.9 | 4.2 | 9.8 | 2.6 |
| Joint buying | 0.4 | 1.8 | 2.9 | 6.8 | 1.1 |
| Joint production of goods or services | 2.9 | 3.0 | 3.9 | 9.6 | 3.1 |
| Integrated supply chain | 0.9 | 1.3 | 1.2 | 7.1 | 1.1 |
| Joint marketing or distribution | 2.4 | 5.3 | 6.1 | 13.0 | 3.6 |
| Other collaborative arrangements | 1.6 | 1.6 | 2.7 | 4.4 | 1.7 |
| Any collaborative arrangements | 7.8 | 10.1 | 13.8 | 28.7 | 9.1 |

**Table 3: Collaborative Arrangements by Employment Size 2013-14 (Data source: Australian Bureau of Statistics, 2015b)**

In addition to scarce personnel resources, smaller enterprises often have difficulty in accessing capital or financing to support research and innovation activities, and this would appear to have become even harder following the 2008 global financial crisis, further stifling innovation and growth (Lee, Sameen & Cowling, 2015).

Not withstanding the particular difficulties faced by SMEs when wishing to engage with universities and publicly funded research agencies, what actions can be taken to encourage engagement and collaboration?

Franco and Haase's (2015) study of university-industry engagement in Portugal found that

> *"… intermediators such as inter-university agencies, local authorities and professional associations appear to be highly relevant as facilitators enabling U-I* [University-Industry] *cooperation."*

In the USA, Japan and South Korea, partnership 'champions' have been found to play a key role in building the necessary trust relationships, with these champions being key facilitators of the activity, getting the project started, overcoming obstacles, maintaining commitment and dealing with the myriad problems that arise (Hemmert, Bsteiler & Okamuro, 2014). In the United Kingdom, intermediaries who had significant experience working at the academia – industry interface were important in supporting the negotiation process due to their ability to ensure that participants share a common understanding (Al-Tabbaa & Ankrah, 2016). Similarly, a study of activities at Sweden's Uppsala University showed that support staff who had both academic and industrial experience are able to build trust between the academic and industry players, where this trust-building is crucial to establishing effective interactions (Jonsson, Baraldi, Larsson, Forsberg & Severrinsson, 2015). Holt, Goulding and Akintoye (2016) conclude that facilitation activities (including industry engagement along with the time and funding to support it) may be critical to achieving impact from research.

While flexible and transparent intellectual property policies make an important contribution to the development of trust between university and industry partners, effective champions lessen the potential detrimental impact of these policies by keeping everyone's attention focused on efforts to make the collaboration work, rather than the formal rules and policies that will govern it (Bstieler, Hemmert & Barczak, 2015). It is worth noting here that the creators of intellectual property in these projects (the university researchers), may have a different approach to any intellectual property outcomes than their own technology transfer and industry engagement offices. Okamuro and Nishimura (2013) suggest that while academics are usually not interested in the ownership of intellectual property coming out of collaborations with industry, their administrative centres, such as technology transfer offices, often are. From this they conclude that university intellectual property policies are more likely to affect the incentives and commitment of the industry partners more than it affects the commitment of the academics (Okamuro & Nishimura, 2013). It is not unreasonable to infer that research undertaken at universities with flexible and responsive intellectual property policies has a higher potential for achieving impact via the commercialisation pathway.

Worryingly for universities, Collier et al's (2011) study of Australian high-tech SMEs found they tend to have a negative view of technology transfer offices, characterising them as either irrelevant or difficult to deal with, to the extent that when possible they would avoid dealing with them directly. In the United

Kingdom it has been recommended that while the technology transfer offices are playing an important role, for improved collaboration with industry they should prioritise knowledge exchange over shorter-term income generation (Dowling, 2015), presumably to promote ease of interaction. Given the pressure on many universities to generate income from non-government sources this would likely be a source of tension, although as we have seen previously, the reality is that activities such as patenting and licencing are generally poor generators of income for universities.

If it is indeed the case that industry finds university technology transfer offices problematic to deal with, we would expect there is an important role here for facilitators and champions in keeping the research front and centre while sometimes representing both the academic and the industry client to central bureaucracies.

A key feature of effective champions is an ability to bridge the different cultures, mindsets and operating philosophies of academia and industry, coupled with a commitment to the success of the collaboration (Chakrabarti & Santoro, 2004). Perez-Astra and Calvo Babio (2011) define a number of professional competencies and personal characteristics that are required for success in these 'relationship promoter' roles:

> *The very complexity of the functions … and the importance of establishing a network of stable relationships to ensure their success make motivation, responsibility, empathy and extroversion vital personal qualities for these professionals, accompanied by their knowledge and management skills."*

These roles act as an interface between disparate cultures and therefore must be able to view situations from multiple perspectives and act as an effective bridge.

Standing outside a university it can appear impenetrable – how do you express your problem from a discipline perspective and which of the many possible entry points will take you to the best person? Who is the best person? The person with the best academic record in your area may not be the best person to work with your staff on the results you need. As noted by Perkmann, King and Pavelin (2011), it is not always the highest quality ranked academics who are the most successful in forging collaborative relationships with industry, with differences evident across disciplines. In one sense, there is a high probability that a company searching for a collaboration will not find a suitable researcher, nor will an interested researcher find an appropriate company and this results in companies spending time on searches that may result in sub-optimal research partners, or even deciding that it is all just too difficult (Calcagnini, Gioimbini, Liberati & Travaglini, 2016). Mindruta (2013) suggests the industry-university research marketplace is essentially a two-sided matching market, where

> *"The inputs each partner brings to the relationship are highly differentiated: the expertise of university scientists is not a commodity, and neither are the capabilities of individual firms. … The critical question in these markets is who trades with whom."*

This matching is also highly asymmetrical in the sense that the match is often between a company and their problem and an individual researcher, so that the reputation of the institution where the researcher works may be of relatively low importance (Collier et al, 2011), despite the wishes of many technology transfer offices.

The United Kingdom's Dowling Review (2015) concluded that effective brokerage and seed-funding is vital for successful collaborations between industry and academia, especially for SMEs. It is this role of intermediaries as matchmakers and facilitators in the defence research sector that will now be focused on.

*The Defence Science Institute*

In 2011 the University of Melbourne and the Defence Science Technology Organisation (now known as DST group) formed the Defence Science Institute (DSI) with financial support from the State Government of Victoria. The DSI was initiated to support the development of Victoria's defence technology and national security industry through the facilitation of defence focused collaboration, research and engagement between universities, research organisations and industry.

In the Defence Science Technology group, Australia has a well-established organisation undertaking research across a wide range of discipline and application areas in support of national defence and security priorities. With many graduates of Victorian universities working for the DST group there are strong personal links in some areas but it was recognised that across many others there was a lack of knowledge on both sides regarding the expertise held in each organisation and the opportunities for collaboration and contribution. Similarly, many actors in the defence supply chain are unaware of how to access this expertise to help them solve challenges affecting their ability to deliver products and services.

A small unit, staffed by a mix of DST group and university staff and including recruits from government and industry, the Defence Science Institute focuses on facilitation and match-making supported by tools such as small grant programs encouraging collaboration. Crucially, the DSI takes a regional and multi-disciplinary approach to the defence science sector, acting on behalf of all universities within Victoria. This allows it to identify the most suitable academics to address a particular task, regardless of their home institution or discipline, and to pull together strong consortia including relevant industry and government participants. When approached by industry or funding bodies, particularly international bodies, it is able to provide an overview of the strengths and capabilities in regards to defence related research which can be found in the Victorian research community. In this sense, the DSI shares similarities with the Knowledge Integration Community (KIC) model of university-industry engagement developed by the Cambridge-MIT Institute (CMI) in the early 2000s (Acworth, 2008). Apart from the scale of activities undertaken, the major point of departure is where CMI has an ongoing management role in the establishment and operations of the KICs, DSI's role effectively ends once provisional approval for funding has been received.

Stakeholders in the DSI fall into three broad categories: governments and funding bodies; the Victorian higher education sector; and the defence industry sector. The core activities of the DSI are focused on the facilitation and enhancement of defence-relevant research and fostering engagement by

- Identifying defence-relevant research and technology development opportunities;
- Providing advice on the defence research and development environment, both within Australia and internationally;
- Connecting defence and industry to research and development expertise; and
- Promoting and showcasing research and development and innovation capabilities in both the public and private sectors.

The DSI focuses on assisting Defence researchers and funders, Victorian universities and industry to work together to achieve the outcomes each wants (Figure 3). Effectively this is achieved by open and continuous communication, both externally and internally. Visits, meetings, phone calls, presentations and the like are supported by a limited number of tools including:

- Discovery workshops;
- Collaborative Research seed funding grants;
- Postgraduate student support grants;
- Industry internship grants for research students;
- Participation in and hosting of delegates from defence trade missions;
- Training for and hosting of innovation pitches focused on investment; and
- Participation in major defence industry events.

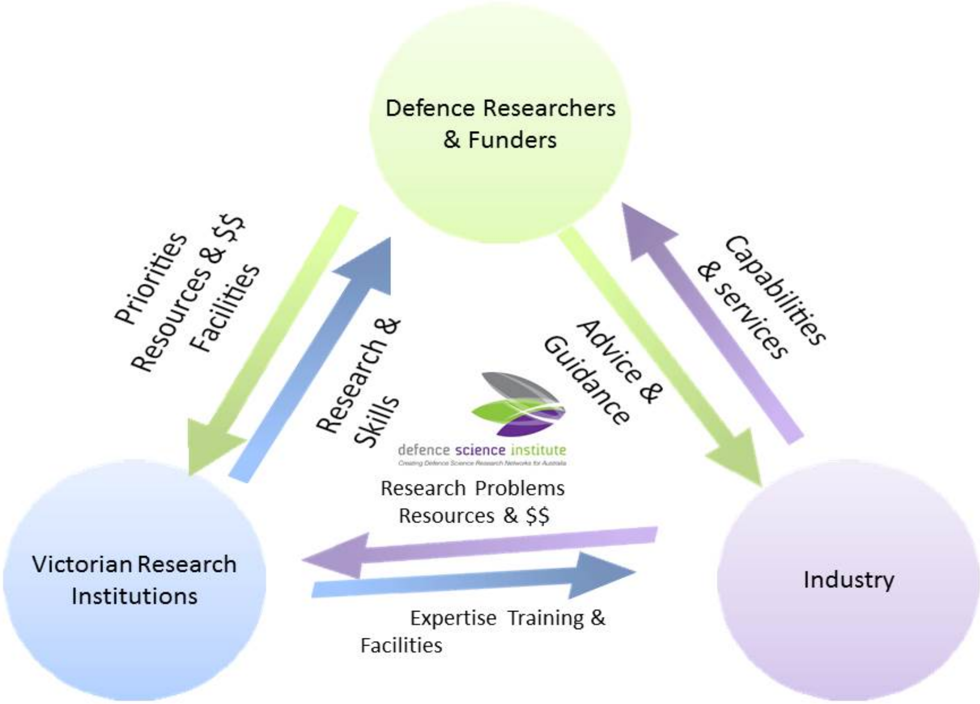


Figure 3: DSI Operational Environment

Taking a sectorial approach to encouraging university-industry interactions can have economic benefits for those universities who implement it. In 2003 Imperial College London introduced a sectorial approach to developing and managing university-industry interactions at a Faculty level. In part, this was to facilitate larger, multi-disciplinary collaborative projects, and contributed to Imperial successfully gaining £20 million in industry-related research funding over five years (Philbin, 2010). A sectorial approach requires investing resources in understanding the sector – who the key players are, their relationships, what are seen to be key challenges and the political landscape in which it operates.

In Victoria, combining the sectorial approach with a regional approach has provided significant benefits for a greater number of stakeholders than just a single university. In five years from 2011, the Defence Science Institute has contributed to the attraction of more than $50 million in Commonwealth Government, international and industry funding invested in the State of Victoria for defence research related activities. Over $10 million of this was achieved as direct co-investments with DSI provided seed grants. Taking into account the industry and inkind investment in DSI facilitated activities, the Victorian Government's investment in the enterprise has received an economic return in the order of $16 for every $1 invested, initiated new collaborations and income streams for Victoria's universities, established new operations locally by international companies and supported the training of postgraduate students across a diverse range of disciplines of interest to defence.

Operating with a multi-discipline focus, the DSI has also played a key role in broadening perceptions within the academic community about what research is relevant to defence. For many people defence research conjures up images of weapons and associated systems – the hardware of war. But modern defence and national security agencies also have a profound interest in the human and wider environmental sides of conflict in all its guises. They fund and collaborate with those working across a diverse range of areas: behavioural psychology, sports science, trauma medicine, human-machine interaction, ethics and law, cultural engagement, cybersecurity, turbulence and flow, virtual reality, biological sensing and fuel efficiency to name a few. Within the university sector, defence funding agencies are interested in supporting work that not only fulfils defence needs but also has applications within the wider community. The reality is that much of the research relating to military hardware and weapon systems is highly classified and inappropriate for undertaking within the open institution of the modern university, but there are many areas where the needs of defence and society in general are essentially the same.

The sectorial approach requires having strong links into each group of stakeholders, a broad overview of what is happening in each of these stakeholder groups and the ability to make connections between pieces of information from a wide variety of sources. As a collaborative approach, the facilitating service must be seen to be neutral, with no agenda of its own, beyond that of providing value for stakeholders. The Defence Science Institute does not undertake any research of its own and works closely with other organisations, such that it is viewed as a neutral and non-competitive actor in the space. As a small unit, it has the flexibility to deploy its limited resources in a strategic way, a practice that is vital to its ability to achieve beneficial outcomes.

A number of countries run grant funding programs specifically aimed at university-industry collaboration, for example, Australia's ARC *Linkage Project* program or the *Danish National Advanced Technology Foundation* program. A study of the Danish program found that while these programs may not necessarily result in increased innovation as demonstrated by patenting rates, in the longer term the capabilities developed by the companies can help them to make more effective decisions regarding applied research activities (Chai & Shih, 2016). Similarly, in Italy, while it would appear that policies fostering industry-university links have not been successful in improving economic gains from the exploitation of academically-produced knowledge:

> *"It is only when entrepreneurship is combined with access to scientific knowledge and universities are prone to collaborate with external parties that their ventures may significantly stimulate growth"* (Carree, Malva & Santarelli, 2014).

In the experience of the DSI, there is a ready market for small, targeted grants to help kick-start collaborations, but without a facilitation function, there is the risk that these collaborations are opportunistic and may not lead to long-term relationships. Facilitators assist in identifying the most relevant collaborative partners, both from a technical and cultural point of view. For industry players looking for academic researchers, recommendation by an independent facilitator implies that the academic in question will not only be able to address the problem, but they will also be able to work with industry, something that not all academics are comfortable with. For academics, facilitators can identify other academics to add value to their projects, potential sources of funding and help find champions for projects within the funders.

For the DSI, in addition to supporting industry engagement, a key role has emerged in facilitating research collaboration between the government's own defence research body and universities. In contrast to the defence research bodies of many of its allies, Australia's Defence Science and Technology group outsources a relatively low proportion of its research and development budget, between five and ten percent. Its UK equivalent, the Defence Science and Technology Laboratory spends more than 75% of its budget on externally sourced research. For the US Naval Research Laboratory this figure is more than 50%, while for Japan's Technical Research and Development Institute it is around 80% (Callinan & Gray, 2015). From the low outsourcing level we can infer there is scope for Australia's defence agencies to take increased advantage of the intellectual capabilities found within the university sector.

DSI's role in facilitating research collaboration between DST and universities also highlights a factor which is often ignored when discussing wider academic engagement and moving research outcomes into the community. These discussions are generally expressed as university-industry engagement. But in reality, we are talking about university-non-university engagement. As noted by Hughes and Kitson (2012), the public sector, and to a lesser extent the non-profit sector, contribute to advances in both innovation and quality of life. In the United Kingdom, while there are differences between the discipline groupings, overall, academics interact more with both the public sector and the charitable sector than they do with the private sector (Hughes & Kitson, 2012). Only for the STEM disciplines is private sector engagement higher, which may be a reflection of STEM's greater use of commercialisation practices such as patenting and licensing.

The DSI has succeeded in facilitating collaboration and attracting investment to the State of Victoria by applying limited resources within a defined geographic area. What, then, is the potential outcome of increasing the scale of the model?

The question of scaling can be approached in two main ways. Scaling by increasing the resources available is unlikely to result in a linear increase in results due to the limits imposed by the size of the sector, both geographically and in terms of participants. However, staff of the DSI would no doubt agree that an increase in resources would allow them to both improve current activities and develop new initiatives leading to outcome growth.

Scaling can also be considered in regards to the geographical area covered. To date, the DSI has had a small geographic focus, the State of Victoria. It is currently looking at how the model might be applied on the national level, possibly through a connected network of state-based organisations sharing a number of services. Taking this facilitation model national is in response to the DST group wishing to increase its engagement with universities in other states and a desire expressed by international bodies that they would prefer to be able to access information about all of Australia's capability through a single entry point.

The limiting factors to scaling up this model of activity and retaining optimal efficiency are likely to be geographic spread and sector size. Geographically, Australia's defence and research communities are dispersed over a wide area, with local clusters in particular regions. This can provide challenges in regards to building the personal relationships and maintaining the knowledge base necessary for successful facilitation, requiring a lot of travel and heavier reliance on telecommunications and planned interactions. However, in terms of the number of participants and the economic activity involved, the communities are small enough for a relatively small team to be able to service the sector. In contrast, the United Kingdom has a relatively small geographic spread with a larger sector, while the USA has both a large geographic spread and a large sector. This suggests that while for Australia and the UK, a nationally focused operation may be optimal, for the USA it may be better to focus on individual or small groups of, states.

The Imperial College example (Philbin, 2010) shows that taking a sectorial approach to defence research engagement can be very successful for an individual university. The DSI example demonstrates that expanding this model to act on behalf of members of a geographical region benefits the region. Taking a sectorial approach to industry engagement is quite common for individual universities: technology transfer and business development offices will often arrange their staff in teams which successfully focus on a range of individual industry sectors. Can the collaborative regional approach be successfully applied to sectors other than defence?

A country's defence sector can be defined as having a single market customer – the government – with suppliers including multinational corporations, local SMEs and other governments. Defence operations occur in stressful environments, necessitating detailed specifications for performance. Crucially, for most developed nations, the development of research solutions to 'market' problems, are undertaken or mediated by defence research organisations. Usually constituted as part of the Department of Defence or equivalent, these research organisations play a vital role in formulating the needs of the defence forces as a research question and in testing and validating presented solutions. In this sense, they act as a single entry point to the various branches of defence for other research providers and are able to bestow vital credibility in regard to academic research and the solutions it brings. Within the Australian context, entities such as the various rural R&D corporations (for example, Dairy Australia, Meat & Livestock Australia and Australian Wool Innovation) are also well placed to fulfil this role across the agricultural sector.

The single research entry point for other sectors can be difficult to define. In Australia, the National Health and Medical Research Council (NHMRC) distributes research funding, provides advice and produces clinical practice guidelines based on research evidence. As such it would appear to be the prime candidate for playing the same role as DST group in a health facilitation application of the DSI model. But the NHMRC is a Commonwealth body and the delivery of health services is largely a State responsibility in Australia. In addition, there are already strong links between individual universities and research and teaching hospitals. In the health sector, the difficulties would appear to be more around facilitating translation and implementation rather than facilitating research partnerships. In Queensland, this is being addressed by the activities of the Australian Centre for Health Services Innovation (AusHSI). With a focus on integrating research findings in to policy and practice, as part of its activities AusHSI administers grants on behalf of the Queensland Department of Health. One stream of grants is to undertake studies on the implementation and evaluation of research-based practice in hospital or clinical settings, thereby providing an evidence base for interventions[15]. Initiated as a partnership between the Queensland Government, two of Queensland's universities and Queensland's premier research and teaching hospital, AusHSI demonstrates the growing recognition that collaborative approaches involving actors from government, industry and academia have a great deal to offer in regards to ensuring strong societal returns from investments in publicly funded research. As a collaborative approach operating within a specified geographical area, the AusHSI is a similar model to that of the DSI, targeting a different point on the research-development-innovation continuum.

For many sectors, government are neither the main client nor the main service provider, but there may be industry associations that can undertake the DST group role in a collaborative facilitation activity. In the main, industry associations primarily act as lobby groups, with many also providing ongoing education services. Nevertheless, associations are able to provide the insights to the industry landscape that are crucial for successful engagement. Associations are neutral players in regards to the individual interests of their members, focused as they are on collective needs. Associations which include a focus on industry sustainability as part of their mission are particularly well-placed to being working with universities to facilitate sectorial relationship building and providing an additional service to their members.

[15] http://www.aushsi.org.au/funding/information-about-funding accessed 30th August 2016

# Chapter 7: Indicators of Potential Impact

Many of the measures that are routinely collected by research organisations, while not measuring actual impact, can be indicative of the potential ways in which a given research activity may have an impact in the future. It is important to recognise that there are no indicators which will be applicable to all research, nor are various indicators necessarily comparable. The greatest value of indicators may by in helping to identify interesting case studies and in supporting the value of those case studies.

## 7.1 Bibliometrics, Scientometrics & Citation Analysis

*"If citations are what you want, devising a method that makes it possible for people to do the experiments they want at all, or more easily, will get you a lot further than, say, discovering the secret of the Universe"*

- Peter Moore, Yale University (as quoted in *Van Noorden et al, 2014*)

Bibliometrics, scientometrics and citation analysis are terms which are often used interchangeably. De Bellis (2009) states that while there is considerable overlap between bibliometrics and scientometrics, bibliometrics is concerned with the collection and analysis of any statistical information relating to publications such as books and journals. In contrast, scientometrics focuses on specific information that has been judged as being important and relevant for the comparative evaluation of various entities contribution to the advancement of knowledge. Common metrics used in scientometrics outside publication data include those relating to international collaborations and practitioner mobility.

Citation analysis is essentially a tool for obtaining indications of the quality (as defined by its usefulness) of a particular piece of research based on referencing practices in the academic literature – referencing practices which constitute a particular form of social behaviour within the research community (Moek, 2005). While it is proving popular with many of those who manage research, and especially groups of researchers, traditional citation analysis is of limited benefit to those attempting to assess the wider impact of a research activity.

In 2005, Hirsch proposed the *h*-index as a measure of the productivity and academic impact of individual researchers. In the intervening years a number of limitations have been identified for the index, along with modifications to overcome these (for a summary of these see Panaretos & Malesios, 2009). Despite these limitations, the *h*-index, and its offshoots, have gained popularity as a single measure indices for use in the ranking of individuals and its use has also been (controversially) extended for the ranking of research groups and university departments.

While funding bodies, governments and promotion panels all want a simple single metric to use when comparing the quality and impact of researchers and research groups, the use of citation analyses such as the *h*-index has not been universally accepted by researchers themselves (Panaretos & Malesios 2009). Shortly after the introduction of the *h*-index van Raan (2006) urged caution,

> *"… it is not wise to force the assessment of researchers or of research groups into just one specific measure. It is even dangerous, because it reinforces the opinion of administrators and politicians that scientific performance can be expressed simply by one note. That is why we always stress that a consistent set of several indicators is necessary, in order to illuminate different aspects of performance."*

Sarli et al (2010) suggest that in medical research, traditional citation analysis significantly under-estimates the impact of research, ignoring outputs and outcomes such as practice guidelines, curriculum guidelines, ancillary and new research studies, legislation and regulation, newsletters, industry publications, and web tools (part of the 'grey literature'). Van Eck, Waltman, van Raan, Klautz and Peul (2013) refine this suggestion to conclude that standard bibliometric analysis underestimates the citation impact of clinical research in comparison to basic and diagnostic research.

Many national research quality assessment exercises emphasise publication venue as a measure of the quality of research, with favourable weightings for papers published in high impact international journals. Yet, when looking at species recovery plans for conservation, an area where research can have significant impact, Calver, Lilith and Dickman (2013) found that around 40% of citations found in plans were from the 'grey literature', such as reports and student theses. In addition, depending on the source country, a relatively low 27% to 42% of the journal papers cited are found in the top quartile of *SCImago* ranked journals (Calver et al, 2013). The formulation of species recovery plans will be a highly localised activity and as such is likely to rely heavily on research published in commissioned reports and national rather than international journals. In this sense, research outputs are likely to be lowly ranked in terms of research excellence, but all would agree that research which influences the way in which we manage endangered species has the potential for high impact. While this may be a relatively extreme example, it does highlight the potential for research quality and research impact assessment exercises to be focused on contradictory outputs. ICT research which contributes to industry standards will have a significant impact in the marketplace, yet may be ignored by the research literature. Quality research, as often measured by citation analysis, is not always impactful research and vice versa.

While not always easy to define, the grey literature in some instances may be a more efficient dissemination mode if you want to see research impacting on the wider community. The grey literature is often an under-represented research output in traditional bibliometrics, scientometrics and citation analysis.

The US National Institute of Environmental Health Sciences (NIEHS) has recently looked at automating the assessment of impact from its grants by examining the references found in 'important' grey literature (for example: policies, clinical guidelines, regulations, expert panel reports) and linking them to NIEHS grants (Drew, Pettibone, Owen Finch III, Giles & Jordan, 2016). While case studies supported the results produced by the automated process, Drew et al (2016) do note that the method is subject to similar strengths and weaknesses as when applying bibliometrics to the scientific literature.

Regardless of this, it is encouraging to see a funding agency exploring relatively inexpensive ways of determining the wider impact of their activities.

Traditionally, assessment has focused on either discipline/academic impact or economic impact (Butler, 2008), and while in some disciplines traditional citation analysis will give an indication of impact as a proxy for research quality, this is not the case in all. In many instances, the link between discipline/academic impact and wider impact is also not clear.

For individual researchers, the calculated value of indices such as the *h*-index, can vary greatly depending on the data set interrogated. Thomson Reuters is the predominant source of citation data via products such as the *Web of Science* and *Web of Knowledge* indexes. While much improvement has been made in recent years, it has long been recognised that disciplines disseminating knowledge predominantly through conferences rather than journals (such as computing science) find the *Web of Science* citation data of limited value (Moed & Visser, 2007).

This highlights one of the major difficulties in utilising traditional citation metrics in a field such as ICT, with practitioners from many disciplines and with varying dissemination and citation practices. Developers of citation analysis indices stress the inappropriateness of using these tools to compare researchers across disciplines. In actuality, the research community is made up of myriad sub-communities, each with their own set of norms in relation to how their results are disseminated and how they acknowledge each other's work. These differences become increasingly apparent when considering multi-disciplinary activities.

### *7.1.1 Case Study – Interdisciplinary Publishing at the University of Melbourne's Centre for Neural Engineering*

Impact factor has become an influencing factor in where researchers elect to publish their work and also in the evaluation of researchers and research groups. Individuals are encouraged to target high impact venues and the impact factor of these venues has become a shorthand way of estimating the quality of researchers, both as individuals and groups. Editors use the impact factor to sell their journal as the publication venue of choice for quality researchers and breakthrough ideas. This establishes a reinforcing cycle – influential researchers publish in high impact journals where the impact remains high due to the calibre and influence of the researchers publishing in them.

The best known comparator of journal impact is probably Thompson Reuters' *Journal Impact Factor* (JIF), drawing on citations recorded in the *Web of Science* citation database. Other comparators include *SCImago Journal Rank*, *Eigenfactor* and *Source Normalised Impact per Paper* (SNIP). Comparators vary in the citation datasets used, journals included, calculation methods, time frames included, and attempts to account for variations in citation practices between disciplines. This is a deliberate use of the term comparator. An impact factor number on its own tells us very little. It is only by knowing where it stands in comparison to similarly themed journals that the score acquires any sort of meaning.

As impact factors are generally calculated from citation counts over specified time periods they are highly influenced by the citation practices within particular disciplines:

> *"… articles in biochemistry often contain over 50 cited references, while a typical mathematical paper has perhaps only 10. This difference is an important factor explaining why biochemical papers are cited so much more often than mathematical ones."* (Moed, 2016)

The size of the publishing community in disciplines can also vary greatly. As such there can be a significant difference between the impact factor score of the top ranked journal in biochemistry compared to the top ranked journal in mathematics. Normalised journal impact metrics such as *SCImago Journal Rank* and *Source Normalised Impact per Paper* (SNIP), attempt to account for discipline differences and tend to provide journal quality assessments that are more in line with those reached by expert assessment (Ahlgren & Waltman, 2014). However, as noted by van Eck, Waltman, van Raan, Klautz and Peul (2013) these field-normalised indicators do not correct for the variety of citation practices which may exist within the field and thus may not be as accurate as is generally believed.

Given these limitations, what does impact factor actually tell us? After all, given the ease with which online publishing allows us to collect a variety of metrics relating to individual journal articles, journal level metrics may be approaching their use-by date. Early development of the JIF in the USA was driven by a desire to formulate an unbiased, quantitative method of identifying the key journals that resource-limited science and engineering libraries should then prioritise for purchasing (Archambault & Larivière, 2009). Some of the criticism directed at the JIF – dominance of English-language and particularly US journals, poor coverage of the humanities – can be traced to the distance its usage has moved from its original purpose.

At one level, impact factor is a proxy for circulation that attempts to include a measure of the quality of that readership. As any newspaper editor knows, it is not just the number of readers that you have but also the demographic of that readership that determines your advertising rates and ability to influence society. High impact scores send a message that not only is this the journal you should be reading but it is the journal that is read by those who will pay attention to your research. Publishing in high impact journals increases the visibility of an individual piece of research and this in itself can lead to more citations.

Emphatically, journal impact factors do not tell us anything about the quality or usefulness of the research reported in any individual paper other than the editors and reviewers think it is of better quality than other papers which were submitted but not accepted for publication. In this sense it acts as a proxy indicator of popularity based on the reputation and practices of a publishing venue, much like university entry scores can reflect course popularity as much as they reflect the level of intellectual rigour involved. High impact journals will have higher numbers of papers submitted to them and thus get to select the highest quality for publication. This does not mean that any individual paper will be deemed to be high quality and thus highly cited. Indeed, by definition, at least half must be cited less than the journal median and it has been suggested that impact factor is a poor predictor of eventual citation success (Seglen, 1994; Finardi, 2013; Prathap, Mini & Nishy, 2016). Tsai (2014) suggests that when calculating the *h*-index for high impact factor computer science journals, there is low correlation between the two citation measures. Tahamtan, Safipour Afshar and Ahamdzadeh (2016) report three categories of factors which affect the number of citations a paper will receive: paper-related; journal related; and author related. As part of their review they identified 28 factors which, to varying degrees, tend to result in more citations. Many of these do not necessarily relate to the quality of the work itself. Yet there can be a tendency to infer from the impact factor of a particular journal the quality of the researchers who are accepted for publication within that journal and of individual papers.

It may be that we have already passed the point of maximum correlation between journal impact and paper and research quality as indicated by citation rates. Lozano, Larivière and Gingras (2012) found that since the move to electronic dissemination of scientific knowledge in the early 1990's, the relationship between the citation rates of individual papers and the impact factor of the journals they are published in has been breaking down. They suggest this may be due to the ease with which specific articles can now be found online, regardless of the journal in which they are published, compared to the limitations of searching through only the physical journals that you have access to. Over time, bibliographic index journals such as Current Contents, Chemical Abstracts and Biological Abstracts have morphed in to online databases. Long gone are the days when deciding what paper to read was based on the title and author as listed in a Current Contents copy of a journal contents page and if your library had a physical copy. Search engines such as *Google Scholar* provide universal coverage of academic work, regardless of the format in which it is outputted, or the bibliographic database it is captured in.

The 2012 *San Francisco Declaration on Research Assessment*[16] specifically calls for journal-based metrics, including JIF to not be used as

[16] www.ascb.org.dora, accessed 30th March 2013

*"…a surrogate measure of the quality of individual research articles, to assess an individual scientist's contributions, or in hiring, promotion, or funding decisions."* (DORA, 2012).

Similar concerns were raised by the UK House of Commons Science and Technology Committee (2011) after they found that even for high impact journals chance plays a role in any individual article being accepted for publication. Concerns have also been raised about the reliability and accuracy of the calculation of journal impact factors. Greenwood's (2007) analysis of research and experimental medicine citations found that while for the top (and possibly the bottom) tier of journals, the calculated impact factor and subsequent journal ranking is accurate, for the majority of journals this is not the case. Errors in the JIF calculation could result in significantly variable placements in the ranking table (Greenwood, 2007). This accords with Pajić's (2015) finding that the ranking of journals can be unstable depending on factors such as indicator used and the resulting conclusion that apart, from the divisions between those journals ranked at the top compared to the bottom, quality assessment, and hence ranking, often assumes that a very small change in the number of citations has a large effect.

It has been suggested that for medical research high impact factor journals may have low levels of relevance for clinical practice and that clinical research articles experience a citation lag that is disadvantaged by calculation methods (Kodumuri, Ollivere, Holley & Moran, 2014). Suhrbier and Poland (2009) note that

"… *publications with profound benefits for health or science may not* [be published in high impact factor journals] *(inter alia Gardasil and DNA sequencing);…".*

suggesting that merely relying on where a researcher publishes could even disadvantage Nobel prize winners. It has also been suggested that reliance on journal impact factors and rankings may discourage interdisciplinary research in areas where top-ranked journals tend to accept more single-discipline papers

(Rafols, Leydesdorff, O'Hare, Nightingale & Stirling, 2012) which could have implications in regards to high impact research.

Despite the difficulties associated with journal impact comparators they continue to be used, often by those without a thorough understanding, as a shorthand means to judge researchers. Because of this, impact factors can drive changes in dissemination behaviour.

*The Centre for Neural Engineering*

The University of Melbourne's Centre for Neural Engineering brings together researchers from such diverse fields as psychiatry, neurology, electrical engineering, bioinformatics, physiology, physics, nano-engineering, stem cell biology and computing. Publication and citation practices vary widely across these fields, with significant differences between Journal Impact Factor measures for leading journals in each discipline as well as between *h*-indexes for those recognized by their peers as leaders in their fields. From *Web of Science* data, Bornmann and Marx (2015) calculate the citation impact factor of engineering and technology papers published in 2007 to be 10.77, while that for medical and health sciences over the same period was much higher at 16.85, reflecting differing citation practices and community sizes.

Table 4 shows Thomson Reuters *Web of Science* journal citation data for the year 2012 for a range of journal categories in which publication venues for the Centre for Neural Engineering are classed: the number of journals included in each category, the total number of articles published across those journals during the year, the total number of citations of those articles and the calculated median and aggregate impact factors. The number of journals within each category varies markedly, as does the average number of articles per journal. Just as there are significant differences in the median and aggregate impact factors for each category, so too are there significant differences between the impact factor for individual journals within each category (Table 4).

| Category | Total Cites | Median Impact Factor | Aggregate Impact Factor | # Journals | Articles |
|---|---|---|---|---|---|
| AUTOMATION & CONTROL SYSTEMS | 143277 | 1.219 | 1.810 | 59 | 6840 |
| CELL & TISSUE ENGINEERING | 64364 | 3.873 | 5.319 | 17 | 2140 |
| COMPUTER SCIENCE, ARTIFICIAL INTELLIGENCE | 229977 | 1.232 | 1.860 | 115 | 9988 |
| COMPUTER SCIENCE, INTERDISCIPLINARY APPLICATIONS | 225983 | 1.328 | 1.812 | 100 | 11518 |
| ENGINEERING, BIOMEDICAL | 272114 | 1.583 | 2.869 | 79 | 10279 |
| ENGINEERING, ELECTRICAL & ELECTRONIC | 808651 | 1.103 | 1.629 | 243 | 42571 |
| ENGINEERING, MULTIDISCIPLINARY | 116451 | 0.707 | 1.128 | 90 | 9876 |
| IMAGING SCIENCE & PHOTOGRAPHIC TECHNOLOGY | 61967 | 0.876 | 2.073 | 23 | 2132 |
| MATHEMATICAL & COMPUTATIONAL BIOLOGY | 194930 | 1.606 | 2.742 | 47 | 5499 |
| MEDICAL INFORMATICS | 53223 | 1.603 | 2.005 | 23 | 3078 |
| MEDICINE, RESEARCH & EXPERIMENTAL | 562580 | 2.263 | 3.307 | 121 | 16761 |
| MULTIDISCIPLINARY SCIENCES | 1865672 | 0.603 | 6.803 | 56 | 36788 |
| NANOSCIENCE & NANOTECHNOLOGY | 646528 | 1.792 | 4.706 | 69 | 25353 |
| NEUROIMAGING | 107201 | 1.638 | 4.450 | 14 | 2496 |
| NEUROSCIENCES | 1787981 | 2.872 | 3.983 | 252 | 34432 |
| OPTICS | 467242 | 1.175 | 2.251 | 80 | 23770 |
| PHYSICS, APPLIED | 1234554 | 1.393 | 2.785 | 128 | 47621 |
| PHYSICS, MULTIDISCIPLINARY | 806550 | 1.170 | 2.871 | 83 | 23947 |
| PSYCHIATRY | 616323 | 2.013 | 3.392 | 135 | 13284 |
| TELECOMMUNICATIONS | 149916 | 0.962 | 1.335 | 78 | 11102 |

**Table 4: 2012 Journal Citation Data by Category (Thomson Reuters)**

Electrical engineering and computing researchers often focus on dissemination via conference presentation, with many practitioners having a far greater proportion of conference papers compared to journal articles. For the period 1999 - 2001, conference papers accounted for 45.1% and 62.3% of Australia's university publication outputs in Engineering and Computing respectively (Butler, 2008). In peer assessment, there is consensus around the top ranking conferences, just as there is around the top journals, and conference activity (both as paper authors and members of organising committees) is valued highly. In contrast, biomedical researchers tend to focus on publication in journals and it is not unusual for there to be no significant conferences included in a researcher's publication list. Butler (2008) reports that just over 90% of Australia's publication outputs in Biological and Medical and Health Sciences are journal articles, with book chapters also outnumbering conference papers in frequency. This difference in the importance of conferences is reflected in the differences in which presentations and proceedings are dealt with. Submission, followed by publication, of a full paper is common for engineering and computing conferences, while biomedical conferences are more likely to select presentations on the basis of abstracts which are subsequently published in the proceedings.

When attempting to compare citation rates using indicators such as the *h*-index, the citation database used will also have a profound affect. *Web of Science* citation data is journal-centric, with relatively few established conference series or books included (although Thomson Reuters has now introduced the *Book Citation Index* as part of its core *Web of Science* offering). In recent years *Scopus* has greatly increased its coverage of peer-reviewed conferences (including IEEE and ACM refereed conferences, venues of choice for many electrical engineers and computer scientists) and academic books. With its web-based approach, *Google Scholar* includes many sources of non-academic citation such as inclusion in textbook lists and references in general news articles, but has been subject to criticisms regarding the quality and consistency of citation data retrieved, particularly in its early years (Jacso, 2005), and the ease with which it can be manipulated (Delgado López-Cógar, Robinson-García & Torres-Salinas, 2014). While *Google Scholar* is considered to include too many duplicate citations, *Scopus* and *Web of Science* are thought to omit up to 10% of article citations from their databases (Franceschini, Maisano & Mastrogiacomo, 2015). In addition to these three main multi-disciplinary citation databases there a number of smaller, discipline focused databases such as *Medline* and *Embase.*

The number of journals and items covered by individual citation databases can vary considerably. Of the major subscription databases, *Web of Science* covers around 13,600 active scholarly journals compared to *Scopus* coverage of almost 20,350, both of which are far short of the 63,000 journals recorded by Ulrich's

Periodical Directory (Mongeon & Paul-Hus, 2016). In 2008 Iselid reported that journals covered by both citation databases represented 54% of *Scopus* coverage, but 83% of *Web of Science* coverage, corresponding with *Scopus*' greater listing of journals overall. Iselid (2008) also found that neither database fully covered the content of discipline focused databases *Medline* or *Embase*, although the gaps in coverage by *Scopus* were far smaller compared to *Web of Science*.

Given the differences in coverage size for *Scopus* and *Web of Science*, it is to be expected that the coverage of Ulrich-recorded periodicals is greater for *Scopus*, but there are differences in how the two databases cover various fields. For example, coverage of Natural Sciences and Engineering journals is similar: *Scopus* 38%, W*eb of Science* 33%, but coverage in Biomedical Science is quite different: *Scopus* 48%, W*eb of Science* 28% (Mongeon & Paul-Hus, 2016). In addition, as we saw above, the journals themselves which are included can be quite different.

These differences in journal and source coverage can result in significant differences in the citation counts recorded for individual researchers which are not consistent across disciplines. While *Scopus* and *Web of Science* produce similar citation numbers for life sciences researchers, for engineering researchers *Scopus* provides a slightly greater than 25% increase in citations compared to *Web of Science*. For humanities researchers the increase is almost 40% (Harzing & Alakangas, 2016). As noted by Butler (2008), when the journals included in a particular database cover less than one fifth of research output (as is the case for computing research in Australia) the use of standard bibliometric measures cannot be supported.

For ranking or comparative purposes within a single discipline it may not matter so much which database is used, rather which indicator is measured or calculated. Franceschet (2010) found that for a group of Italian computer scientists

> *"…Google Scholar computes significantly higher indicators' scores than Web of Science. Nevertheless, citation-based rankings of both scholars and*

*journals do not significantly change when compiled on the two data sources, while ranking based on the h-index show a moderate degree of variation."*

This is consistent with Meho and Rogers' (2008) study of internationally renowned human-computer interaction researchers' citations and *h*-index calculations from *Scopus* and *Web of Science*. Similarly, a 2008 study of Israeli researchers across a number of fields found that the database chosen affects the calculated *h*-index (Bar-Ilan, 2008).

This all suggests that whenever a researcher includes their *h*-index on their resume they should include the data source and the number of documents surveyed, but this is not often seen. It also suggests that when assessors or recruiters are attempting to rank people it is better to be based on citation counts, taken from the same database, and not calculated *h*-indexes, especially if those indexes have been supplied by the researchers themselves and may be calculated from non-comparable sources. It has been suggested by Harzing & Alakangas (2016) that provided either *Scopus* or *Google Scholar* are used as the source of citation data, the proposed *hIa* index, which takes into account the number of co-authors and the length of the author's academic career, may be a valid comparator for evaluating researchers across the disciplines of Science, Engineering, Social Science and Life Science. However, their conclusions are drawn from a sample of senior academics at a single university and require further testing (Harzing & Alakangas, 2016).

These issues surrounding discipline practice and citation database coverage are critical as to why the use of citation indexes in making management decisions at the institutional or above level is fraught with difficulty. But the information held in these databases can provide interesting insights as to how publication behaviour can change when researchers become involved in interdisciplinary research.

*Publication Behaviour*

For the Centre for Neural Engineering, composed predominantly of engineers and biomedical researchers, it would appear it is the engineers who have taken on the publication practices of their biomedical colleagues rather than the other way around (Figure 4).

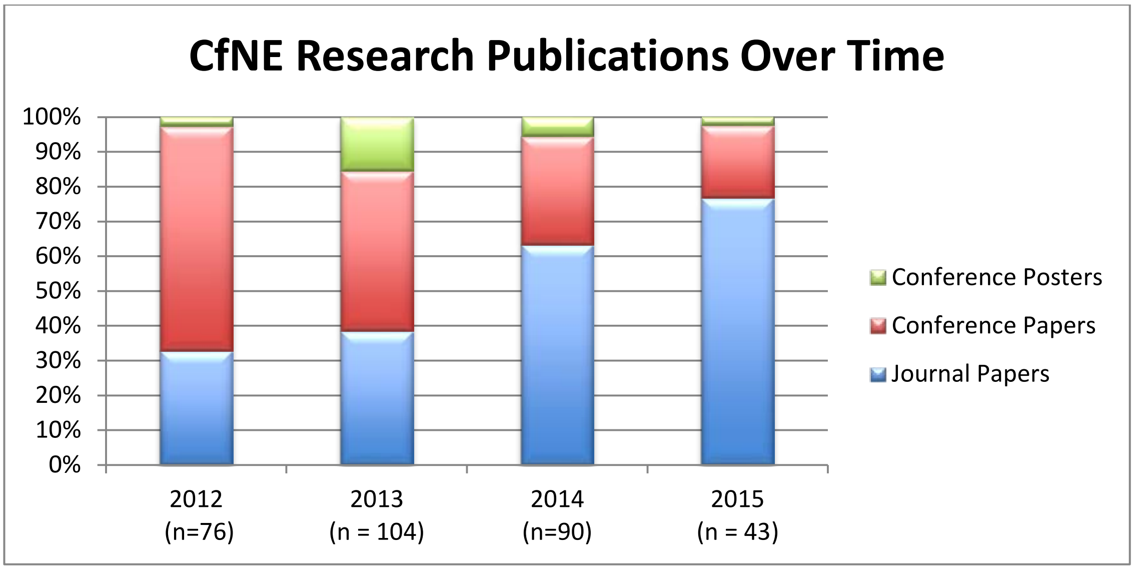


**Figure 4: Change in CfNE Publication Type over Time**

During the period January 2012 to August 2015, 313 research publications were produced with author affiliations including the Centre for Neural Engineering: 155 journal articles, 134 conference papers and 24 conference posters. Over time there has been a consistent move towards publication via journal articles – from 33% in 2012 to 77% for the first 8 months of 2015.

Along with this change in type of publication venue, there have also been changes in the disciplinary classification of journals, conferences and books as recorded within *Scopus* (Table 5, Figure 5). For the full years 2012, 2013 and 2014, the number of publications captured by *Scopus* is relatively constant at 85, 86 and 83 respectively. Partial year data for 2015 is included to provide an indication of trends for the year. It must be noted that publication venues can be included under more than one disciplinary classification, and one could argue that the increase in captured classifications themselves (from 141 in 2012 to 171 in 2014) for similar numbers of publications is in itself an indication of increasing cross-disciplinarity.

| SCOPUS DISCIPLINARY CLASSIFICATION | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|
| Engineering | 48 | 47 | 28 | 9 |
| Medicine | 14 | 23 | 29 | 9 |
| Neuroscience | 10 | 10 | 21 | 8 |
| Computer Science | 34 | 34 | 20 | 7 |
| Biochemistry, Genetics and Molecular Biology | 2 | 4 | 18 | 9 |
| Physics and Astronomy | 20 | 23 | 14 | 8 |
| Materials Science | 7 | 16 | 10 | 9 |
| Agricultural and Biological Sciences | 1 | 2 | 8 | 2 |
| Mathematics | 1 | 6 | 7 | 0 |
| Arts and Humanities | 1 | 4 | 3 | 0 |
| Chemistry | 0 | 2 | 3 | 2 |
| Environmental Science | 1 | 1 | 3 | 0 |
| Multidisciplinary | 2 | 2 | 2 | 1 |
| Pharmacology, Toxicology and Pharmaceutics | 0 | 0 | 2 | 0 |
| Social Sciences | 0 | 0 | 2 | 0 |
| Health Professions | 0 | 0 | 1 | 0 |
| Psychology | 0 | 0 | 0 | 1 |
| Chemical Engineering | 0 | 4 | 0 | 1 |
| Immunology & Microbiology | 0 | 0 | 0 | 1 |
| *Total Classifications* | *141 (85 pubs)* | *178 (86 pubs)* | *171 (83 pubs)* | *67 (29 pubs)* |

**Table 5: SCOPUS Disciplinary Classifications for CfNE Publication Venues 2012 – 2015**

Over the period there has been a decrease in publications classified as engineering or computer science while there has been a corresponding increase in those classified as medicine or various biomedical disciplines. This shift in discipline publication is not unique to the CfNE: Bishop, Schuyler, Huck, Ownley, Richards and Skolits (2014) found a similar shift in the early years of the National Institute for Mathematical and Biological Synthesis (NIMBioS) at the University of Tennessee. In the NIMBioS case, publication increased in mathematical science venues as classified under the ISI *Web of Science* (Bishop et al, 2014).

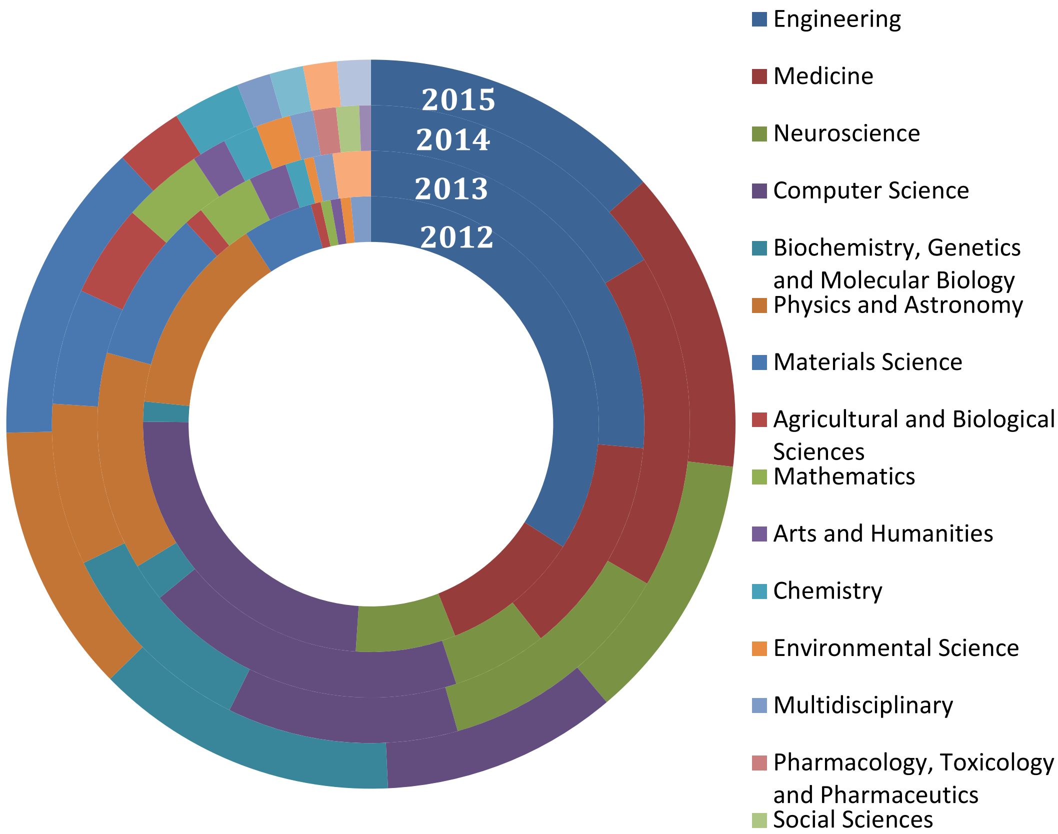


**Figure 5: SCOPUS Publication Venue Discipline Classification for CfNE Publications 2012 - 2015**

The effect of cross-disciplinary centres on research productivity as measured by publication output is unclear. Bishop et al (2014) found no increase in publication numbers for participants joining NIMBios. This, they noted, was in contrast to earlier reports by Garner, Porter, Newman and Crowl (2012) and Ponomariov and Boardman (2010) that association with an inter-disciplinary research centre results in significant increases in publication rates. While an in-depth analysis has not been made for the publication rates of CfNE personnel before and after their affiliation, the relatively steady number of publications captured by *Scopus* would suggest little change in productivity in the early stages of the Centre.

If involvement in interdisciplinary centres results in changes in publication behaviour what are the factors that drive these changes?

Administratively, the Centre for Neural Engineering sits within the School of Engineering with staff, support and funding also being contributed by the

Faculties of Science and Medicine, Dentistry and Health Sciences. In the first two years of its existence, the Centre also had a number of participating staff, along with financial support, from the Victoria Research Laboratory of National ICT Australia Ltd (NICTA VRL). This meant that, initially, personnel, including graduate students, were predominantly drawn from the engineering disciplines, particularly those associated with ICT research.

In regards to publication disciplines, most personnel began to use their CfNE affiliation from the moment they joined the Centre. This meant that early publications will have been the result of work undertaken prior to joining and may have limited cross-disciplinary collaborations. As the proportion of personnel from a non-engineering background has increased, so too has the proportion of non-engineering classified publications, as cross-disciplinary projects develop and mature. Engineering is considered an applied science, and in the case of the CfNE, engineering approaches and techniques are being applied to neural systems and networks. Thus it should not be surprising to see publications appearing in venues that engineers traditionally do not publish in. Publication in journals with different discipline categories to that associated with individual researchers is not uncommon. Depending on the discipline, up to 59% of social science and humanities publications may be published in 'out-of-discipline' publications (Haddow, 2015).

So much for the change in venue discipline. But why has there also been a change in the type of publication venue? There are likely to be two main contributing factors.

Conferences have long been popular computer science and engineering venues of choice for the dissemination of results. While varying between sub-disciplines, it is estimated that from 30% to 80% of computing science papers are published at conferences where they are fully refereed and may be publishing mature research results in comparison to that published many other disciplines in conference venues (Godoy, Zunino & Mateos, 2015; Wainer, Eckmann, Goldenstein & Rocha, 2013). For this reason, decision makers such as Deans and Heads of Departments have tended to pay relatively little attention to indicators such as Journal Impact Factor when assessing performance. Rahm (2008) found that for the top 100 cited conference series included in the *Microsoft Libra* computer science database the average number of citations per paper is similar to that of the top 100 cited journals suggesting there is no advantage to publishing in journals. Similarly, Freyne, Coyle, Smyth and Cunningham (2010) found that for the leading conferences, citation rates were comparable with mid-ranking journals. There tends to be consensus within the community as to which are quality conferences, but as yet, despite limited attempts such as *CiteseerX* Venue Impact Factor, no one has been able to formulate an equivalent "Conference Impact Factor".

Dissemination via conference tends to allow information to spread more quickly than traditional journal publication. Computer science emerged as a rapidly changing discipline in the 1950's, at the same time as air travel was opening up to the masses. Previously, attendance at international conferences could require a researcher to be away from their laboratory for weeks or even months, such that there could be a large time cost in regards to publishing via this route. It should be noted that the availability of accepted and pre-print papers online has lessened the dissemination time advantage previously held by conferences over journals. Turnover time for reviewing and manuscript preparation now largely determines the time taken for dissemination, something that can be the same for a conference or a journal. Coverage of conference publications by the main citation databases *Scopus* and *Web of Science* is improving and for some disciplines, conferences still remain the main publication venue.

By contrast, in the biomedical research community, publication via journal is generally considered preferable to that of conference, although there are conferences that will publish their proceedings as a special issue of the associated journal. This preference for journal dissemination means that it is not unusual to find biomedical researchers who are more aware of the impact factors of journals they are looking to publish in than their engineering counterparts.

For Centre for Neural Engineering researchers, this greater awareness of and emphasis on Journal Impact Factor by colleagues, collaborators and a major stakeholder may have helped reinforce a trend towards more journal publications. At the same time, a major source of financial support for conference travel was lost (especially for students). Attendance at international conferences in Europe and North America is a significant investment for Australian researchers and with decreased funding available, researchers have little option but to turn to journal dissemination. Given the concurrent nature of these two events, it is impossible to say with certainty which was the dominant factor in the move away from conference publication to journal publication, following on from the changes in venue category.

*Multi-Disciplinary Research and Citation Impact*

In terms of academic impact as measured by citation rates, involvement in the multi-disciplinary Centre would appear to provide greater benefit to the engineers (Table 6). Keeping in mind that not all papers will include authors from mixed discipline backgrounds, those CfNE papers which are published in the biological, medical and health or psychology and cognitive sciences categories tend to achieve greater field-weighted citation impact and citations per publication than those in the engineering, physical sciences or technology categories.

| Journal Category | Publications | Citations | Authors | Field-Weighted Citation Impact | Citations per Publication |
|---|---|---|---|---|---|
| All Categories | 294 | 1292 | 702 | 1.36 | 4.4 |
| Biological Sciences | 35 | 360 | 386 | 2.61 | 10.3 |
| Medical & Health Sciences | 108 | 798 | 457 | 1.83 | 7.4 |
| Psychology & Cognitive Sciences | 18 | 396 | 61 | 3.79 | 22 |
| Engineering | 137 | 322 | 285 | 1.13 | 2.4 |
| Physical Sciences | 89 | 218 | 119 | 1.16 | 2.4 |
| Technology | 38 | 243 | 257 | 1.54 | 6.4 |

**Table 6: CfNE Citations by Journal Category (Data source: SciVal analysis of Scopus data as at 21 Sept 2015)**

In addition to the contribution of the paper to current research dialogues, citations per publication will also reflect the publishing and citation practices associated with disciplines publishing in that category and the size of the research community working in that topic space. Field-weighted citation impact attempts to take these factors in to account, but nevertheless, direct comparisons are fraught with difficulty. Notwithstanding this, it is reasonable to infer that a CfNE engineer co-authoring a paper that is published in a biomedical journal has a greater increased likelihood of being cited than a CfNE biomedical co-author on a paper published in an engineering journal. Waltman, van Ran and Smart (2014) report that health and life sciences publications which include terms relating to engineering and the physical sciences in their titles and abstracts will often have a citation impact above that of their discipline average, so then engineers publishing with their biomedical colleagues in biomedical journals could expect to receive a boost to their citation performance.

This differential effect on citations depending on the home discipline accords with that reported by Larivière and Gingras (2010) who found that humanities papers citing medicine papers are themselves more likely to be cited more than average, while the reverse does not hold. Later work has suggested that the areas of chemistry, brain research and biology tend to receive the greatest boost in citations from collaborations outside the discipline (inter-disciplinary), while the humanities and electrical engineering and computer science tend to be penalised the most when undertaking collaborations within their sub-disciplines (intra-disciplinary) (Larivière, Haustein & Börner, 2015). Similarly, Chen, Arsenault and Larivière (2015) report that

> *"… the increase of papers' citation rates as a function of interdisciplinarity is higher for subfields with lower citation rates … than for subfields with higher citation rates, … This suggests that, by citing papers from other disciplines and specialties … papers become more associated to the fields they cite rather than to the journal in which they are published and, hence, are more likely to obtain the citation rates of the fields they cite".*

Larivière et al's (2015) analysis was based on the network of citations across disciplines contained within individual publications and this may account for the difference in relative benefits. Bibliometric analyses of interdisciplinary research often determine the nature of the inter-disciplinarity of the work by categorisation of the references cited. Using this approach, Yegros-Yegros, Rafols and D'Este (2015) suggest that

> *"…: each of the attributes of diversity [variety, balance, disparity] has a different effect on citation impact. … These results suggest that papers with a clear disciplinary focus and a small proportion of references to many proximal disciplinary categories, are comparatively more cited. Thus there is no simple relation between IDR* [interdisciplinary research] *and citation impact".*

Obviously, one does have to be very careful when making generalisations about the potential for participation in interdisciplinary research to result in increased impact. When interdisciplinary research changes the ways in which work is published and disseminated there is the potential for the work to be viewed in a new context by a different audience. Exposure to a wider audience should result in increased opportunities for ideas and people to connect, potentially leading to new innovations. Increased collaboration, as indicated by publishing with larger numbers of co-authors, is also often associated with increased citation rates (Godin & Gingras, 2000; Mirnezami, Beaudry & Larivière, 2016) and this may partially be a result of larger, established networks.

## 7.2 Patents & Licencing

*"Shall an invention be patented or donated to the public freely?... The answer is very simple. Publish an invention freely, and it will almost surely die from lack of interest in its development. It will not be developed and the world will not be benefited. Patent it, and if valuable, it will be taken up and developed into a business."*

- Elihu Thomson, Acting President, MIT, Address to the Graduating Class, 1920

Like all metrics relating to components of a complex ecosystem, patenting data provides valuable information, but does not tell us everything we want to know. Not all patent applications are granted full patents, and while the utilised portion is higher, not all granted patents make it to the market place. Like any relatively simple metric, patenting activity can be manipulated: rich research institutions can lodge applications that they know have little chance of being granted in order to inflate the numbers. Large corporations can buy patents from small inventors with the express aim of preventing them from getting to market and competing with their own product.

While discussing the usefulness of patenting and licencing as indicators of impact it is worth keeping in mind that a number of studies have found that patenting and licencing play a relatively small role in the transfer of public research to industry. Cohen, Nelson and Walsh (2002) report that the main ways in which university research impacts industry R&D are via published academic papers, reports, conferences and technical meetings, consulting and informal exchanges. In the US, approximately 15% of industry R&D projects make use of university research. Depending on the sector this proportion can rise to more than 30%, but regardless of the proportion, patents and licences have consistently been considered less important than the four channels above (Cohen, Florida, Randazzese & Walsh, 1998). Hughes and Kitson (2012) report that just over 10% of UK academics across all disciplines are involved in patenting or licensing activities, while D'Este and Patel (2007) state that over half interact with industry through meetings and conferences or consultancy and contract research. Gilman and Serbanica's (2014) review of a number of UK studies led them to conclude that technology transfer activities are the least common form of industry engagement, accounting for less than 3% of external funding. A 2000 survey of mechanical engineering, electrical engineering and computer science academics at Massachusetts Institute of Technology (MIT) found they considered patenting a relatively unimportant method of transferring knowledge (representing less than 10% of the knowledge transferred), with one respondent pointing out that very few companies founded from MIT inventions actually hold a patent from MIT (Agrawal & Henderson, 2002). Agrawal and Henderson (2002) also found that, in general, companies that cite MIT patents do not cite MIT research papers, nor act as co-authors on MIT research papers.

Further to the above observation concerning MIT patents, studies of inventions coming out of Stanford and Columbia universities indicate that when inventions are well developed (basically ready to use straight out of the laboratory) patents and exclusive licences are not important for the transfer of the technology to industry with the IP rights allowing the university to generate revenue but not helping to take products to market. However, in situations where there is a significant amount of development required, IP rights and exclusivity appear to have a greater influence persuading companies to make that investment (Colyvas, Crow, Gelijns, Mazzoleni, Nelson, Rosenberg & Sampat, 2002).

Despite these apparent discrepancies between university patenting and industry uptake, patent information can provide insights for those examining the impact of publicly funded research. Comins (2015) examined data such as assignees and citations for patents resulting from research funded by the US Air Force Office of Scientific Research (AFOSR) and found that while relatively few ended up assigned to private companies, patents that cited the originals were overwhelmingly in the hands of private enterprise. From the data, Comins (2015) was able to identify a case study, tracing AFOSR funding to a small number of highly-cited patents which underpinned a start-up company later acquired by a large technology service provider on the basis of its technologies.

This suggests that while, for universities at least, patenting and licencing data may be of limited value as an impact metric, it can inform the selection of case studies and provide valuable evidence in their support.

In regards to patenting it is interesting to note that one popular method used by governments to encourage industry innovation – the R&D tax credit – may not have any effect on patenting levels. A Norwegian study found that while projects receiving R&D tax credits were associated with process innovation, and to a lesser extent, new products for internal use, there was a negligible effect on patenting or the development of new products for the marketplace (Cappelen, Raknerud & Rybalka, 2012). In China, government institutional support can be associated with lesser innovation in regards to products even though patenting activity itself may increase with the support advancing science and technology in general but also distracting companies from developing patented knowledge in to new products (Shu, Wang, Gao & Liu, 2015).

If the subsidy or reward system is only focused on patenting activity then the incentive is to develop and support applications, rather than utilising those patents to their full potential. Patent subsidy schemes in China are estimated to have resulted in an increase of more than 30% in patent numbers, but this has been accompanied by a decrease in both quality and the breadth of patent claims (Dang and Motohashi, 2015). Dang and Motohashi (2015) suggest that while examination fee subsidies have lifted the rate at which patents are being granted, this is largely due to more lower-value or lower quality patents being put forward for examination, effectively removing the filtering effect that these costs previously applied and greatly increasing the workload of examiners. This increase in quantity at the cost of quality in response to incentives echoes that previously seen in academic publishing in Australia (Butler, 2003; 2003a).

Clearly, if increasing patenting activity, as a proxy for innovation, is the goal of government interventions, programs must be carefully formulated and targeted.

In common with the academic literature, patenting literature practices citation, both of other patents and of academic literature. A given research project may result in either a patent itself or an academic paper which is later cited in another patent. These patents may then go on to be cited in further patents, rippling out in widening circles of impact.

There are indications that patent citation rates correlate positively with company performance and export volume (Neuhäusler & Frietsch, 2012; Frietsch, Neuhäusler, Jung & Van Looy, 2014; Neuhäusler, Frietsch, Schubert & Blind, 2011). This suggests that being able to identify contributing patents and publications will provide us with some indication of impact. But as we have seen previously for academic publications, citation data is highly dependent on the source, such that comparisons must be approached with care. It would appear that the same is true when considering patent citations. Bakker, Verhoeven, Zhang and Van Looy (2016) report that differing data sources and ways of calculating patent citations, such as the filing office, the use of patent families and only including granted patents, can result in significant differences in the citation indicators calculated. They note that while it is assumed that different calculation methods for patent citation indicators will generally give similar results, it may be that patent citations calculated from different offices may reflect national rather than global impact (Bakker et al, 2016).

It has been suggested the inclusion of specific citations within a patent may be a reflection of the way in which patent writers view the document and hence are motivated in regards to citing:

> *"… if we view a patent as a type of specification document, then papers cited in the patent could be analyzed similar to those cited in journal articles. However, if we view the patent as a legal document, which defines rights and focuses on the patent's claims, then papers cited in the patent would carry specific legal functions prescribed by patent law. We could also view the patent as a type of economic interest document, which describes the product's benefits versus competitors and its potential marketability."* (Li, Chambers, Ding, Zhang & Meng, 2014).

Just as academic disciplines vary in their citation practices, so too it would seem that patent offices and examiners do too, with corresponding differences in the patent data held. Data from the United States Patent and Trademark Office

(USPTO) covers different geographic areas to that held by the European Patent Office (EPO) and there is evidence that EPO patent examiners tend to include fewer citations than examiners from the USTPO (Bakker et al, 2016). Also, as noted by Messeni Petruzelli, Rotolo and Albino (2015), patent influence as determined from citation data varies across industrial and organisational domains.

From this it is reasonable to infer that caution should be exercised when using patent citation data as an indicator of impact, just as with traditional bibliometric data. Li et al (2014) suggest the prevailing motivation for citing other patents determines the usefulness of the analysis, especially when attempting to trace the linkages between scientific research and technological innovation, with economic motivations more likely to involve criticising other patents rather than acknowledging their influence.

Patent numbers and licencing income are just two of a suite of technology transfer indicators that tend to be focused on traditional formal methods and may drive organisations to limit the types of activities they undertake (Sigurdson, Sa & Kretz , 2015). Whether or not this is actually the case, traditional technology transfer indicators may underestimate the impact of other transfer processes. For example, the use of open source is well established as a dissemination method for software and the maturation of 3-D printing technologies is now beginning to establish free and open-source hardware (FOSH) as a potential driver of distributed manufacturing, particularly for highly customised, low-volume items (Fisher & Gould, 2012; Wittbrodt, Glover, Laureto, Anzalone, Oppliger, Irwin & Pearce, 2013). Pearce's (2015) study of an open source pump design led him to conclude that

> *"The case study presented found millions of dollars of economic value from a relatively simple scientific device being released under open-licenses. This represents orders of magnitude increase in value from proprietary development. It is clear that FOSH development should be funded by organizations interested in maximizing return on public investments*

*particularly in technologies associated with science, medicine and education."*

Record keeping regarding open source transfers varies – some items require a form of licence, others can just be downloaded and shared freely. Open source transfers are one mechanism which can support 'permissionless innovation'. The most visible example of permissionless innovation is the creation of apps for use on devices using android and iOS operating systems. The applications are not developed by Google and Apple, developers and owners of the operating systems, rather they have freely released the necessary application programming interfaces for use by others without them needing to negotiate access first (Chesbrough & Van Alstyne, 2015). As noted by Chesbrough and Van Alstyne (2015), permissionless innovation results in an increase in the speed of invention and allows the innovation ecosystem to generate ideas that were not envisaged by the system designers. Permissionless innovation is a manifestation of the question asked in Chapter 4.9 – are researchers themselves necessarily the best people to recognise the potential impact of their work?

Permissionless innovation as an extension of 'freely revealed proprietary information' is well established within the IT sector – the open source software movement has been with us for a long time and in 2005, IBM issued a statement declaring that it would not assert its rights for 500 US patents if they were being used in open source software (IBM, 2005). It has been used in the mining sector and there have been suggestions that pharmaceutical development and health care could benefit, although here the argument appears to be based more on the decreased regulation aspect of permissionless (Chesbrough & Van Alstyne, 2015, Adams, 2015). The growth in open government data repositories and associated competitions encourages use of collected data in innovative ways without necessarily needing to request permission.

For those tasked with tracking the outcomes and impacts of a research breakthrough, movements such as permissionless innovation provide significant challenges due to the lack of formal transactions involved and increased potential for attribution and acknowledgement to not occur.

## 7.3 Industry Development & Employment

Publicly funded research directly provides jobs within the research areas being supported. However, governments are far more interested in the development of new industries or the transformation of those which may be in decline and jobs which may be created from this. There is however, a fundamental tension that can arise between industry development and job creation when that development is based on technological innovation.

In recent decades, much industry development and resultant economic growth has been driven by productivity gains. Increases in productivity arise from the ability to produce more outputs using less units of input, often labour. Essentially, many productivity gains are the result of improvements in efficiency. Many technological innovations that increase productivity do so by automating tasks. In the 1980s and 1990s manufacturing was transformed by the introduction of robots undertaking physical tasks such as welding and painting. Evermore sophisticated algorithms and machine learning techniques are beginning to automate routine cognitive tasks, with the World Economic Forum (2016) estimating that over four million routine office and administrative jobs could be lost over the next five years. Spitz (2004) suggests that while computer technologies complement the undertaking of non-routine cognitive tasks by workers, it often substitutes for those workers performing routine manual and cognitive tasks. In this way, capital investment in technology lessens the ongoing expense of labour for certain tasks and increases productivity. Industry development and transformation that is based on automation therefore can result in the loss of significant numbers of jobs within that industry.

The industrial revolution resulted in the loss of numerous jobs and industries that no longer exist. The introduction of the motor car led to many occupations relating to carriages and horses only existing to serve a hobbyist market. Occupations are in a continual state of flux as technology and society changes. While there is expected to be a decline in available office and administrative jobs in the coming years, this is expected to be accompanied by increasing demand in other areas such as business and financial operations, with data analytics and specialised sales roles becoming particularly important (World Economic Forum, 2016).

During the 1980s growth in jobs was matched by a growth in the skills and education needed for those jobs, with unskilled jobs in decline. In the 1990s this changed, with the fastest growth occurring in highly skilled jobs, modest growth in low skilled jobs and the slowest growth occurring in those requiring middle levels of education (Autor, Katz & Kearney, 2006). This 'hollowing out' of mid-skill level jobs suggests that for industry to continue be competitive it must have access to highly skilled individuals and the training of doctoral graduates through the research system is likely to increase in importance.

How then should researchers articulate the potential for industry development and employment that might arise from their work? For those working in technological fields this may not be easy. After all, their research could lead to changes which result in three people being able to do the work which previously required fifteen. Manufacturing is particularly sensitive to this effect – the number of people employed in manufacturing is now quite small compared to the number of goods manufactured each year. For a region that has just lost 450 jobs following the closure of a manufacturing plant, the promise that a piece of research will lead to a spinout company that might grow to twenty employees is not much consolation. However, this may just be the reality of the new economy for many societies. Rather than having a small number of large employers underpinning the local economy, there will be myriad micro, small and medium enterprises making up a far more variable economy.

One way in which industry development can be realised by research is through contribution to the skills base, particularly for new technical areas. It is this relationship between research and training that will now be examined.

## 7.4 Training & Skills Transfer

Possibly the greatest impact that publicly funded research has on the wider community is through the training of qualified research masters and doctoral graduates. In 2011, almost 90,000 doctorates were awarded by OECD countries (OECD, 2011). Many of these students will have been supported in their endeavours by public funding and all will have contributed to the world's store of knowledge. In many countries, doctoral students are both the beneficiaries of public research funding, both directly and indirectly, and a key input to the nation's research effort.

### *7.4.1 Case Study – NICTA VRL Cohort of Research Higher Degree Graduates*

Australia, in common with many nations, is facing an increasing demand for Science-Technology-Engineering-Mathematics (STEM) qualifications in the workforce. Deloitte Access Economics (2014) found that 82% of surveyed employers "*agreed that people with STEM qualifications are valuable to the workplace, even when their qualification is not a prerequisite for the role*" with 45% expecting their need for STEM skills and qualifications to increase in the near future. This increased desire for STEM-qualified personnel will be due to a number of factors, but with just over 70% of those same employers believing those with STEM qualifications are able to adapt to business change and the same number nominating their own STEM-qualified personnel as being amongst their most innovative, it would appear employers recognise the value of STEM in a rapidly changing and increasingly competitive environment, regardless of the sector.

This increased demand for STEM is occurring as Australia continues to see an overall decline in the proportion of students studying STEM subjects in their final year of secondary school. Kennedy, Lyons & Quinn (2014) report that over the period 1992 to 2012 rates of participation fell by between 5% (Chemistry and Multi-disciplinary Science) and 11% (Intermediate Mathematics). The only STEM subjects which did not record a decrease in participation were Earth Sciences, with a 0.3% increase, and Entry Mathematics with an 11% increase. Interestingly, the percentage increase in Entry Mathematics was matched by an

11% decrease in Intermediate Mathematics participation, a greater decrease than in Advanced Mathematics over the same period (7%). Mack and Wilson (2015) report that in NSW the proportion of Higher School Certificate (HSC) students achieving Australian Tertiary Admission Ranking (ATAR) scores without studying any maths or science more than doubled between 2001 and 2014: from 2.1% of male students and 5.4% of females to 5.9% of males and 14.6% of females. While the percentage of females studying no science has remained constant at around 50%, those taking no maths has almost tripled. Similarly males taking no maths has tripled from 3.1% to 9.3%, while the proportion taking no science has actually fallen slightly from 42.6% to 38.4% (Mack & Wilson, 2015). In accordance with Kennedy, Lyons and Quinn (2014), Mack and Wilson (2015) found that of those studying mathematics, around half are taking the elementary course, which does not include concepts such as calculus. From this they conclude

> *"… it is clear that some 50% of the entire HSC cohort is now ill-prepared to understand any argument presented to them that depends on an understanding of rates of change in scientific data."* (Mack & Wilson, 2015).

Taken together, the Kennedy, Lyons and Quinn (2014) and Mack and Wilson (2015) analyses suggest the decline in secondary school STEM study is largely due to the abandonment of mathematics study, particularly at more advanced levels. Mack and Wilson (2015) note that in the decade prior to 2001 almost all students sat at least one mathematics subject as part of the NSW HSC. Neither maths nor science studies are compulsory in the final years of secondary schooling in a number of Australian states, with varying mathematics requirements in the others. It has been suggested the removal of compulsory mathematics from the NSW HSC in 2001 has been a significant factor in the decline of mathematics study in that state (Wilson, Mack & Walsh, 2013).

While participation continues to decline the rate at which it does so has generally eased since 2002 (Kennedy, Lyons & Quinn, 2014). But as noted by Mack and Wilson (2015), this decline has occurred at the same time as the number of students staying on for the last two years of secondary schooling has been increasing.

Along with this decrease in STEM participation at the senior secondary school level there has been a significant decrease in the proportion of students completing Bachelor-level degrees in Information Technology (IT). Data collected by the Australian Department of Education and Training shows the number of students graduating in IT halved over the period 2004 to 2013 (Department of Education and Training 2004 – 2013). Against a backdrop of increasing participation in tertiary education this has seen IT's graduate share drop from 9% to 3.6% of annual graduations. Over the same period, Engineering and Related Fields maintained its share of undergraduate training at approximately 6% (Figure 6).

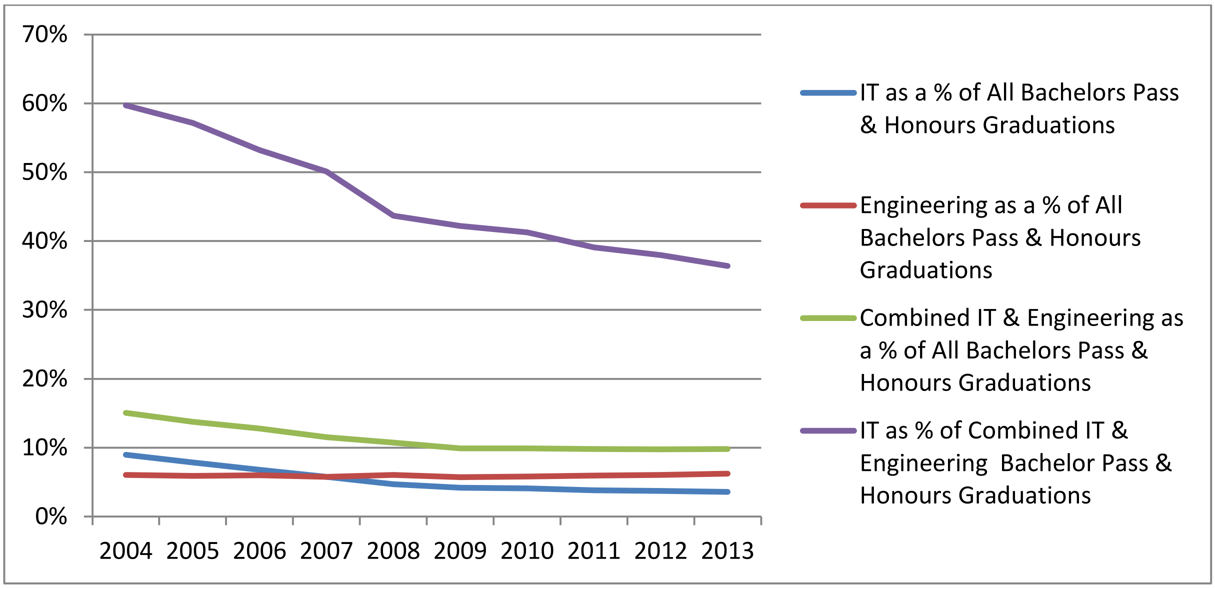


**Figure 6: Australian IT and Engineering & Related Bachelors Pass and Honours Completions 2003 – 2013 (Data Source: Department of Education and Training *Selected Higher Education Data – Student Statistics*)**

This confluence of increasing demand for and decreasing participation in training and skillsets that are considered increasingly important to sustainable economies has prompted Government policy and program interventions at both the national and state level. *Backing Australia's Ability* (Commonwealth of Australia, 2001), introduced by the Howard Government, was an initial 5-year strategy committing AUD$2.9 billion in new funds for science, technology and innovation that included

> "*$176 million for world class centres of excellence in the key enabling technologies of Information and Communications Technologies (ICT) and biotechnology*".

These centres of excellence were intended to have strong industry participation and undertake world-class research and development with an emphasis on generating commercial outcomes and spin-out companies.

The ICT centre of excellence which emerged from the *Backing Australia's Ability* initiative was National ICT Australia Ltd (NICTA). Initially a consortium involving the governments of the Australian Capital Territory (ACT) and New South Wales (NSW) and the Australian National University (ANU) and the University of New South Wales (UNSW), it eventually expanded to include governments and universities from other states, most notably Victoria and Queensland.

NICTA was expected to play a key role in the training of research higher degree (RHD) students, providing increased opportunities for students to work on industry-oriented problems and in teams. In the period 2003 to 2013, 385 research higher degree students associated with NICTA graduated from Australian universities, with an additional 300 expected to graduate over the period 2014 – 2017 (National ICT Australia, 2014).

When the Victorian government elected to become involved with NICTA in 2004, the potential for capability building through research higher degree training was a key consideration, aligning with state priorities for economic development.

Without access to the mineral reserves enjoyed by many other Australian states, manufacturing has played a significant part in Victoria's economy for much of the 20$^{th}$ century. Manufacturing in Victoria has been largely focused on food; automotive and transport; textiles, clothing and footwear; chemicals;

pharmaceuticals; and aluminium. As of 2009 it was the largest employment sector in the state (Parliament of Victoria, 2010).

Manufacturing's share of the Australian economy has been steadily declining over the last 50 years. From a high point of 25% of GDP, employing a quarter of the workforce in the 1960's to 12.5% in the 2000's, employing one tenth of the workforce, this decline has been felt keenly (Productivity Commission, 2003). The decline has continued into the current decade, falling to 7% of GDP in 2014 (World Bank, 2015). Almost 50% of jobs in textile, clothing and footwear manufacturing were thought to be lost in Victoria over a single ten year period (Parliament of Victoria, 2010). It is estimated that in 2012 more than 260,000 Australian jobs were involved in automotive manufacturing and its associated supply chains, largely based in Victoria and South Australia, with many at risk following announcements by major car manufacturers regarding their intentions to downgrade their Australian operations (Allen Consulting Group, 2013).

With traditional manufacturing in decline, high-tech industries with a strong ICT component are seen as a viable alternative for some economies to transition to. For every new job created in traditional manufacturing it is estimated that 1.2 to 1.6 additional local service jobs are created (Parliament of Victoria, 2010; Moretti, 2010). This is in comparison to the five additional jobs, including two professional jobs, created by each new high-tech job in metropolitan areas, according to Moretti (2010).

In 2009 - 2010 the Victorian Parliament Economic Development and Infrastructure Committee undertook an inquiry into manufacturing in the state. The Committee recognised the increasing importance of advanced manufacturing and also found that

> *"Fostering an innovative environment through the availability of skilled labour; support for research and development; and a strong legal and business environment should be an ongoing priority for the Commonwealth and Victorian Governments to ensure medium to high technology manufacturing firms are encouraged to invest in the Australian*

> *manufacturing sector*" [Finding 15 (Section 4.2.9)](Parliament of Victoria, 2010).

By this time the Victorian Government had been investing in a local branch of National ICT Australia in partnership with the University of Melbourne for five years, with key performance indicators including the training of research higher degree students. The Victorian Government also required a significant segment of this training and associated research be undertaken in the emerging area of convergent ICT-life sciences, working with the state's internationally recognised biomedical research sector.

For any government facing changes in the structure of its economy, capability building in regards to higher degree qualifications will be of most benefit if those graduates are diffused throughout society rather than concentrated within academia, the traditional employer of those with research higher degrees. To this end, the Victorian government also desired to have these new doctorate holders encouraged to move in to industry employment.

In addition to increasing general capability within industry, research higher degree holders play an important role in industry-university engagement and collaboration. Collaboration is built on trust and personal relationships as well as expertise. Research higher degree students are able to provide their industry employers with valuable insights as to who really is the best academic to assist with a problem and how to navigate the academia-industry cultural divide.

*NICTA Victoria Research Laboratory Cohort Characteristics*

While eventually the Victorian Government's funding of NICTA would support research higher degree training at a number of universities across the state, the initial years of the venture were focused on training at the University of Melbourne and the cohort examined here are exclusively from this institution.

Enrolment and candidature data for 134 research higher degree students who had been in receipt of a NICTA Victoria Research Laboratory (VRL) stipend at the University of Melbourne during the period June 2004 – May 2015 was collated from the University's student administration system: gender; status in regards to being a local (Australian) or international student; date of enrolment; enrolled department; date of thesis submission (where known); date of candidature completion; degree awarded (Table 7). All had been enrolled as students of two Departments within the School of Engineering: Computer Science and Software Engineering, and Electrical and Electronic Engineering. Employment data was not able to be confirmed for fifteen students (11%), resulting in 119 being used for analysis. All subsequent analyses disregard individuals for whom employment destinations are unknown on the assumption that they display a similar distribution.

| Characteristic | Number | Percentage |
|---|---|---|
| PhD | 108 | 90.76 |
| Masters by Research | 11 | 9.24 |
| Graduated at 31 May 2015 | 116 | 97.48 |
| Thesis Submitted at 31 May 2015 | 3 | 2.52 |
| Male | 95 | 79.83 |
| Female | 24 | 20.17 |
| Local Student at Enrolment | 49 | 41.18 |
| International Student at Enrolment | 70 | 58.82 |
| Enrolled in Dept of Computer Science & Software Engineering | 59 | 49.58 |
| Enrolled in Dept of Electrical & Electronic Engineering | 60 | 50.42 |

Table 7: NICTA VRL Cohort Characteristics (n = 119)

Students had a variety of candidature experiences. While all had at least one supervisor from the University, for many their primary supervisor was a member of NICTA VRL staff. Some students undertook projects as members of larger teams, while for some their research projects were more individualistic. Some student projects involved significant interaction with external collaborators while others were internally focused. A wide range of topics were addressed, including bioinformatics, optics, internet security, microchip design, wireless data transmission, radar, natural language programming, medical imaging, constraints programming, biomedical implants, data mining and network architecture.

The number of months and years of post-study employment was calculated from the date of thesis submission (where known) and the date of successful degree completion to the cut-off date of 31 May 2015. Thesis submission date was not available for all students. In these instances, an estimated submission date of six months prior to successful completion was assumed.

For the 119 students analysed, at 31 May 2015 the mean time elapsed since submission of their thesis for examination was 58 months, or 4.8 years (Table 8). However the time elapsed ranged from less than one month to almost nine years, resulting in a wide range of employment experiences among the cohort.

| | Time Since Thesis Submission | Time Since Successful Completion |
|---|---|---|
| Time Range – Months | 0.37 – 107.70 | 0.13 – 8.25 |
| Time Range – Years | 0.03 – 8.85 | 0.01 – 8.25 |
| Mean Time Elapsed – Months | 58 | 49.3 |
| Mean Time Elapsed – Years | 4.8 | 4.1 |

**Table 8: Time Spent in Workforce by NICTA VRL Cohort Members since Submission and Completion (n = 119)**

*NICTA VRL Cohort Employment*

Employment destinations following thesis submission were tracked via social media application *Linked-In*. Data was also collected or confirmed from employer websites where possible. Students whose thesis had been submitted but not yet passed by examiners at the cut-off date of 31 May 2015 were included, as most students seek to enter the workplace at this time, if not before.

Information available on employer websites and the Australian Securities and Investment Council (ASIC) website was then used to allocate the most recently recorded employer to an industry sector within the Australian and New Zealand Standard Industrial Classification 2006 (ANZSIC 2006) and to a broad category of economic entity. Where employers operated over more than one ANZSIC Division, the allocation was made based on the department or division that the graduate was associated with. Economic entities used were: multinational corporation (MNC); small-to-medium enterprise (SME); start-up; government; university; not-for-profit (NFP); and publicly funded research agency (PFRA).

Based on most recently recorded employer, each student was thus allocated a geographical region; an industry sector and an employer economic unit.

Seventy percent of the cohort were employed within Victoria at their most recently recorded job. The next most common destinations were other Australian states and various countries within Asia at 11% each. Other employment destinations were North America (6%), Europe (4%) and the Middle East (2%) (Table 9).

| Region | Number | Percentage |
|---|---|---|
| Victoria | 83 | 70 |
| Elsewhere in Australia | 11 | 9 |
| Asia | 11 | 9 |
| North America | 7 | 6 |
| Europe | 5 | 4 |
| Middle East | 2 | 2 |
| South America | 0 | 0 |
| Africa | 0 | 0 |

Table 9: Region of Most Recent Employment for NICTA VRL Cohort Members (n = 119)

Some members of the cohort have worked across multiple regions over the time period, with Africa being the only region that no cohort member has recorded employment within.

The academic sector was the predominant employer of cohort members, with 37% employed by universities around the world. Forty-eight percent are employed within the three commercial enterprise units, with the majority of these being with multinational corporations (22%). In Australia, a significant amount of research, particularly biomedical, is carried out within the not for profit sector. Separate to the publicly funded research agencies (for example: CSIRO, DST, ANSTO) these research institutes employed 8% of the cohort (Table 10).

| Economic Unit | Number | Percentage |
|---|---|---|
| University/Academia | 44 | 37 |
| Multi-national Corporation | 26 | 22 |
| Small to Medium Enterprise | 21 | 18 |
| Start-up/Spinout | 10 | 8 |
| Not For Profit | 10 | 8 |
| Publicly Funded Research Agency | 4 | 3 |
| Government | 4 | 3 |

Table 10: Economic Entity of Most Recent Employment for NICTA VRL Cohort Members (n = 119)

Members of the cohort were employed across eight ANZSIC 2006 Divisions: Manufacturing; Information Media and Telecommunications; Financial and Insurance Services; Professional, Scientific and Technical Services; Administrative and Support Services; Public Administration and Safety; Education and Training; and Arts and Recreation Services (Table 11). In the 2011 Australian Census these sectors employed 54% of research higher degree holders in Australia, similar to the 55% in 2006 and slightly below the US figure of 60% in 2013 (Table 15).

| ANZSIC 2006 Division | Number | Percentage of NICTA VRL Cohort |
|---|---|---|
| Manufacturing | 10 | 8.40% |
| Information Media & Telecommunications | 17 | 14.29% |
| Financial & Insurance Services | 5 | 4.20% |
| Professional, Scientific & Technical Services | 40 | 33.61% |
| Administrative and Support Services | 1 | 0.84% |
| Public Administration & Safety | 2 | 1.68% |
| Education & Training | 43 | 36.13% |
| Arts & Recreation Services | 1 | 0.84% |
| **TOTAL** | **119** | **100%** |

**Table 11: Employment of NICTA VRL Cohort Members by ANZSIC 2006 Division (n = 119)**

*Research Higher Degree Holder Employment in Australia*

Data regarding the employment of research higher degree holders across various industry sectors was obtained from 2006 and 2011 Australian Census data using *TableBuilder*[17] (Australian Bureau of Statistics, 2006; 2011). For comparison, corresponding data for the USA was obtained from the 2013 American Community Survey Public Use Microdata Sample (ACS PUMS) using *Data Ferret*[18] (Table 12). United Kingdom census data available via NOMIS does not distinguish between bachelor and above when looking at educational attainment by industry and therefore was not used for comparison[19].

[17] http://www.abs.gov.au/websitedbs/censushome.nsf/home/census
[18] http://www.census.gov/programs-surveys/acs/data/pums.html
[19] http://www.nomisweb.co.uk/

| Australia – 2011 | | | Australia – 2006 | | | USA - 2013 | | |
|---|---|---|---|---|---|---|---|---|
| **ANZSIC 2006 Division** | **Number of Doctorate Employees** | **Percentage of Total Doctorates** | **ANZSIC 1993 Division** | **Number of Doctorate Employees** | **Percentage of Total Doctorates** | **NAICS 2012 Sector** | **Number of Doctorate Employees** | **Percentage of Total Doctorates** |
| Agriculture, Forestry & Fishing | 777 | 0.58% | Agriculture, Forestry & Fishing | 759 | 0.77% | Agriculture | 8,393 | 0.30% |
| Mining | 1147 | 0.86% | Mining | 675 | 0.68% | Mining & Extraction | 4,986 | 0.18% |
| Manufacturing | 2970 | 2.23% | Manufacturing | 2944 | 2.98% | Manufacturing | 164,918 | 5.86% |
| Electricity, Gas, Water & Waste Services | 649 | 0.49% | Electricity, Gas & Water Supply | 430 | 0.44% | Utilities | 6,058 | 0.22% |
| Construction | 621 | 0.47% | Construction | 414 | 0.42% | Construction | 8,545 | 0.30% |
| Wholesale Trade | 1229 | 0.92% | Wholesale Trade | 925 | 0.94% | Wholesale | 15,257 | 0.54% |
| Retail Trade | 1024 | 0.77% | Retail Trade | 864 | 0.87% | Retail | 90,298 | 3.21% |
| Accommodation & Food Services | 486 | 0.36% | Accommodation, Cafes & Restaurants | 273 | 0.28% | | | |
| Transport, Postal & Warehousing | 630 | 0.47% | Transport & Storage | 464 | 0.47% | Transport | 9,601 | 0.34% |
| Information Media & Telecommunications | 1017 | 0.76% | Communication Services | 369 | 0.37% | Information Services | 30,679 | 1.09% |
| Financial & Insurance Services | 2102 | 1.58% | Finance & Insurance | 1581 | 1.60% | Financial Services | 56,781 | 2.02% |
| Rental, Hiring & Real Estate Services | 339 | 0.25% | | | | | | |
| Professional, Scientific & Technical Services | 16564 | 12.42% | Property & Business Services | 12795 | 12.95% | Professional Services | 381,998 | 13.58% |
| Administrative & Support Services | 665 | 0.50% | | | | | | |
| Public Administration & Safety | 8406 | 6.30% | Government Administration & Defence | 6387 | 6.46% | Government & Public Administration | 113,831 | 4.05% |
| | | | | | | Defence | 4,371 | 0.16% |
| Education & Training | 40870 | 30.65% | Education | 30534 | 30.90% | Education | 891,788 | 31.70% |

| Australia – 2011 | | | Australia – 2006 | | | USA - 2013 | | |
|---|---|---|---|---|---|---|---|---|
| **ANZSIC 2006 Division** | **Number of Doctorate Employees** | **Percentage of Total Doctorates** | **ANZSIC 1993 Division** | **Number of Doctorate Employees** | **Percentage of Total Doctorates** | **NAICS 2012 Sector** | **Number of Doctorate Employees** | **Percentage of Total Doctorates** |
| Health Care & Social Assistance | 24064 | 18.05% | Health & Community Services | 17825 | 18.04% | Medicine & Health Care | 472,155 | 16.78% |
| | | | | | | Social Services | 27,808 | 0.99% |
| Arts & Recreation Services | 1175 | 0.88% | Cultural & Recreational Services | 1098 | 1.11% | Entertainment | 38,348 | 1.36% |
| Other Services | 1473 | 1.10% | Personal & Other Services | 1377 | 1.39% | Personal Services | 76,303 | 2.71% |
| Inadequately described | 757 | 0.57% | Non-Classifiable Economic Units | 625 | 0.63% | | | |
| Not stated | 270 | 0.20% | Not stated | 276 | 0.28% | | | |
| Not applicable | 26105 | 19.58% | Not applicable | 18209 | 18.43% | NA | 411,024 | 14.61% |
| **TOTAL** | **133340** | **100%** | **TOTAL** | **98824** | **100%** | **TOTAL** | **2,813,142** | **100.0%** |

**Table 12: Census Data - Doctoral Employment by Industry Sector (Source: Australian Bureau of Statistics, *2006 Census, 2011 Census;* United States Census Bureau)**

Statistical analysis was not carried out when comparing the NICTA VRL cohort to population samples. The small size of the cohort, difficulties in identifying directly comparable sample data and lack of a control cohort suggests that any statistical analysis would not lead to reliable conclusions.

*ICT Research Higher Degree Training in Australia*

Research higher degree training activity in Australia has increased significantly over the last decade: from 6,470 graduations in 2004 across all fields to 9,209 in 2013. This growth has been driven by an increase in PhD completions, with the number of Masters by Research completions relatively constant within the 1,350 to 1,500 range (Table 13). IT and Engineering combined increased as a share of all research higher degree completions from 14.67% to 18.63% over this period.

| Year | | IT RHD Completions | Engineering & Related Completions | Combined IT & Engineering Completions | RHD Completions all Fields | IT & Engineering as a percentage of all RHDs |
|---|---|---|---|---|---|---|
| 2013 | PhD by Research | 313 | 1113 | 1426 | 7787 | 18.31% |
| | Masters by Research | 45 | 245 | 290 | 1422 | 20.39% |
| | Total by Research | 358 | 1358 | 1716 | 9209 | 18.63% |
| 2012 | PhD by Research | 260 | 951 | 1211 | 6847 | 17.69% |
| | Masters by Research | 31 | 212 | 243 | 1383 | 17.57% |
| | Total by Research | 291 | 1163 | 1454 | 8230 | 17.67% |
| 2011 | PhD by Research | 245 | 784 | 1029 | 6524 | 15.77% |
| | Masters by Research | 42 | 0 | 42 | 1437 | 2.92% |
| | Total by Research | 287 | 784 | 1071 | 7961 | 13.45% |
| 2010 | PhD by Research | 229 | 789 | 1018 | 6053 | 16.82% |
| | Masters by Research | 33 | 196 | 229 | 1350 | 16.96% |
| | Total by Research | 262 | 985 | 1247 | 7403 | 16.84% |
| 2009 | PhD by Research | 197 | 704 | 901 | 5786 | 15.57% |
| | Masters by Research | 40 | 185 | 225 | 1296 | 17.36% |
| | Total by Research | 237 | 889 | 1126 | 7082 | 15.90% |
| 2008 | PhD by Research | 218 | 696 | 914 | 5786 | 15.80% |
| | Masters by Research | 31 | 228 | 259 | 1392 | 18.61% |
| | Total by Research | 249 | 924 | 1173 | 7178 | 16.34% |
| 2007 | PhD by Research | 228 | 772 | 1000 | 5721 | 17.48% |
| | Masters by Research | 58 | 230 | 288 | 1392 | 20.69% |
| | Total by Research | 286 | 1002 | 1288 | 7113 | 18.11% |
| 2006 | PhD by Research | 171 | 695 | 866 | 5519 | 15.69% |
| | Masters by Research | 66 | 264 | 330 | 1584 | 20.83% |
| | Total by Research | 237 | 959 | 1196 | 7103 | 16.84% |

| Year | | IT RHD Completions | Engineering & Related Completions | Combined IT & Engineering Completions | RHD Completions all Fields | IT & Engineering as a percentage of all RHDs |
|---|---|---|---|---|---|---|
| 2005 | PhD by Research | 158 | 636 | 794 | 5244 | 15.14% |
| | Masters by Research | 61 | 208 | 269 | 1576 | 17.07% |
| | Total by Research | 219 | 844 | 1063 | 6820 | 15.59% |
| 2004 | PhD by Research | 111 | 571 | 682 | 4900 | 13.92% |
| | Masters by Research | 44 | 223 | 267 | 1570 | 17.01% |
| | Total by Research | 155 | 794 | 949 | 6470 | 14.67% |

**Table 13: Australian RHD Award Course Completions 2004 – 2013 (Data Source: Department of Education and Training, *Selected Higher Education Data – Student Statistics*).**

Department of Education and Training data shows the number of people completing research higher degree training in IT in Australia more than doubled over ten years: from 155 in 2004 to 358 in 2013. For engineering this rate of increase was slightly less: from 794 to 1358 (Table 13).

In 2011 Engineering experienced a drop in research higher degree completions, with a ten-year low of 784 (Figure 7). There is no corresponding decrease in undergraduate completions in the four previous years, rather an increase from 8,075 in 2007 to 9,149 in 2010 (Department of Education and Training, 2003 – 2013).

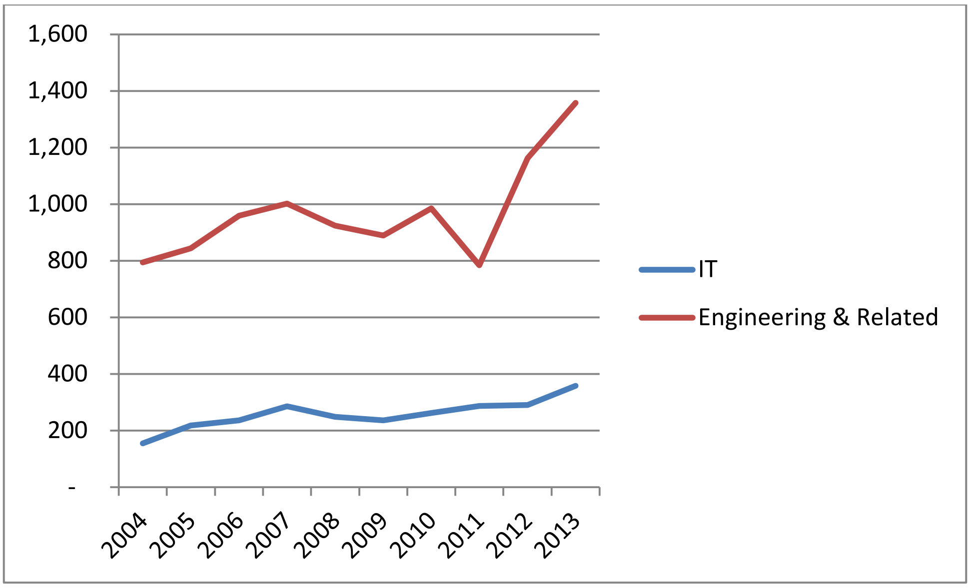


**Figure 7: Australian IT and Engineering & Related RHD Completions 2004 – 2013 (Data Source: *Department of Education and Training Selected Higher Education Data – Student Statistics*)**

Data reported by Kaspura (2011) shows that from 2006 onwards the number of acceptances of offers for places in Engineering courses had increased in line with an increase in both the number of applications and offers made, with the exception of 2008, when a decrease in acceptance rate is observed. Department of Education and Training data confirms that the trend of increasing acceptances did experience a dip in 2008. However, those students completing a research higher degree in 2011 would most likely have begun their undergraduate studies in 2003 or 2004, a time at which acceptances were increasing (Table 14).

| | Acceptances | Acceptance Rate |
|---|---|---|
| **2001** | 7,987 | 72.5% |
| **2002** | 7,934 | 72.9% |
| **2003** | 8,659 | 81.3% |
| **2004** | 8,440 | 80.2% |
| **2005** | 8,439 | 77.2% |
| **2006** | 8,264 | 72.3% |
| **2007** | 9,985 | 82.0% |
| **2008** | 9,287 | 71.5% |
| **2009** | 10,409 | 75.4% |
| **2010** | 10,867 | 77.2% |
| **2011** | 11,150 | 77.0% |
| **2012** | 12,046 | 77.3% |
| **2013** | 12,225 | 77.1% |
| **2014** | 11,503 | 77.3% |

**Table 14: Undergraduate Engineering Acceptance Numbers and Rates 2001 - 2014 (Data Source: *Department of Education and Training Selected Higher Education Data – Student Statistics*)**

Year to year fluctuations in acceptance rates do not appear to result in fluctuations of a similar magnitude when it comes to graduation rates (Figure 8).

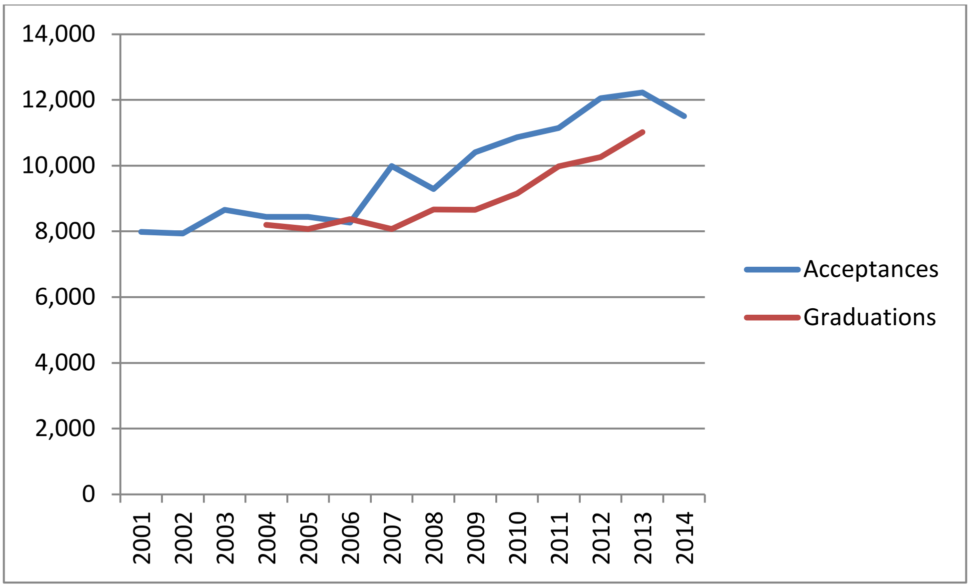


**Figure 8: Undergraduate Engineering Acceptances and Bachelor & Honours Completion Numbers (Data Source: *Department of Education and Training Selected Higher Education Statistics – Student Data*)**

The lack of a corresponding significant drop in Bachelor and Honours completions three to four years prior to 2011 suggests that postgraduate study was an unattractive option for a larger than usual portion of recent graduates at the time. Kaspura (2014) calculates that between 2006 and 2011 employment demand for engineers in Australia increased by 30.8%, an annual compound growth of 5.5%. The years 2006, 2007 and 2008 were also the most volatile in recent years regarding the acceptance rate for those entering undergraduate engineering degrees (Table 14). There is a widespread aphorism that engineers are early indicators of economic activity – first to be hired when things are improving and first to be laid off when the economy is on a downturn. Whether or not there is any truth to this, it may be that the 2011 research higher degree completion anomaly for Engineering was partially due to an increased demand for graduate engineers in Australian industry three to four years earlier.

The increase in IT research higher degree student numbers over the same period has been steadier and is in its own way more interesting. IT has increased both the number of research higher degree graduates and its share of research higher degree graduations across all disciplines at the same time as there has been a significant decline in participation at the undergraduate level: while a smaller number of students are studying IT at university, a greater proportion of these students are going on to postgraduate study. Like the general decline in STEM study, the decline in IT study at the undergraduate level has been a cause for concern as Australian society becomes increasingly reliant on information technology. But there is an apparent inconsistency in our skill development – training at the highest level is increasing, while the level below has been in rapid decline. Maybe the crisis in Australian IT education is not quite as it seems.

Annual IT Bachelor and Honours graduations declined from a high of 12,148 in 2005 to 6,302 in 2013. Over the same time graduations from higher education providers at the Diploma, Advanced Diploma and Associate Degree levels in IT increased by a factor of six, albeit from a very low base (Department of Education and Training, 2004 - 2013). Further study is required before drawing conclusions, but this increase may provide insights as to how the labour market has reacted to the increased demand for IT professionals. Vocational training in information technology is available from a large number of public and private providers and it may simply be that for most IT jobs, a vocational qualification is sufficient, such that those who want to work as IT specialists undertake vocational training while those who are interested in management positions in IT or in R&D undertake bachelor degrees. This raises interesting questions. Did the initial demand for ICT skills outstrip the bachelor supply leading employers to design jobs so that they require vocational qualifications? How does bachelor IT training match up to employer needs? Did an increase in private vocational training providers draw students away from the universities, knowing that the demand for ICT skills was high enough that shorter vocational courses would be sufficient to gain employment?

Despite the increased demand for those with IT training, recent job market experience has been mixed. According to Graduate Careers Australia, just over 68% of 2012 STEM graduates looking for full-time work had found work by April of the following year, down from 2008's high of just over 85%. IT graduates in particular have been facing growing competition from skilled migrants and temporary work visa holders coming to Australia. Birrell (2015) suggests that business strategies around the off-shoring and outsourcing of IT services will continue to put downward pressure on the numbers of entry level IT jobs available in Australia, further discouraging students from undergraduate studies in the discipline. Maybe the future for Australia is more highly qualified IT graduates.

*Sectorial Employment of Research Higher Degree Holders*

Conversations regarding research higher degree holders in Australia often include comments along the lines of "too few of our PhDs are in industry, too many are in academia." Following the steady growth of research higher degree training over the last two decades, questions are now being asked as to how many PhDs are needed: is Australia producing too many? (Group of Eight, 2013). The inference from this is that increasing the number of research higher degree graduates is of limited value if those PhDs work within academia and do not move into industry. From 2006 to 2011 the number of doctoral graduates in Australia as recorded in the census increased by nearly one third, while at the same time there was no real increase in the percentage employed within the

Education and Training sector. Similarly there was no difference in the percentage employed within Government and Public Safety (Table 12). This suggests that thus far, employment for Australia's growing number of doctoral holders continues to follow previously established distributions.

What is not easily discernible is the extent to which industry employment of research higher degree holders in Australia is dependent on push or pull factors. If the assumption is that most research higher degree students are undertaking study with the aim of working in academia, increased competition for those places will eventually result in more people having to turn to industry for employment opportunities. In this scenario, one could expect a significant portion of positions taken up will be ones that industry does not consider to be requiring a research higher degree qualification. In this instance, any increase in industry participation by research higher degree holders is resulting from the increased push into the marketplace. Conversely, if industry decides it requires more research higher degree qualified personnel, it will pull additional PhDs into participation by offering more attractive benefits and working conditions.

But what do we mean when we say we want more PhDs working in industry? When we compare industry participation across countries how do we account for differences in the ways in which traditional employers of research higher degree holders are funded and operate?

In most countries the higher education sector is the largest employer of doctoral holders, both as educators and as researchers. When considering the Australian census, a university employee could state their employment sector as education and training or research services, depending on their exact role. A research-only staff member who is employed on funding from a co-operative research centre, working on a research project sponsored by an industry partner may not consider themselves to work in education and training. A researcher who works for a medical research institute structured as a not-for profit is not part of the government or education sectors, but many would not consider them part of industry. When self-reporting as part of the census even something as simple as public versus private employment can be problematic: are staff in Australia's public universities consistent when choosing between national government, state government or private employment? This public-private distribution will be considered in the next section.

The United States of America is often held up as an example of the rate of industry participation by research higher degree holders that Australia should aspire to. Yet, Australia and the US employ similar proportions of PhD holders in Education, Health Care/Medicine and Social Services. Government and Public Safety employs 6.3% of PhDs in Australia compared to 4.2% in the USA. Taken together, these sectors suggest that the proportion of PhDs employed in industry in Australia is not that different to the USA. Indeed, in certain sectors, such as mining, agriculture and construction, the Australian participation rate by PhDs is slightly higher (Table 12).

Where the USA does do much better than Australia in PhD employment includes the manufacturing and retail sectors. In 2011, the proportion of PhDs employed in manufacturing in Australia was less than half that of the USA and manufacturing's share of PhDs decreased slightly between the 2006 and 2011 census (Table 12). Again we have to question whether the proportion PhDs employed is a cause of or a result of differences in the relative strengths of the sector. While in both countries the proportion of employment in manufacturing is similar – 8.2% in the USA (Henderson, 2013) compared to 8.6% in Australia (Australian Bureau of Statistics, 2011) – US manufacturing makes a greater contribution to GDP, 12%, compared to Australia's 7% (World Bank, 2015). Along with pharmaceutical manufacturing, biomedical device manufacturing is one of the few manufacturing areas in Australia that is not shrinking, and this is the one manufacturing area where members of the NICTA VRL cohort are employed.

The NICTA VRL cohort comprises a specific discipline subset of research higher degree holders and would not necessarily be expected to conform to distribution patterns that arise from a diverse discipline base. Comparisons therefore were made based on a variety of subsets of ANZSIC Divisions, qualifications and fields of study in an attempt to discern valid patterns.

Industry participation of the NICTA VRL cohort was firstly compared with the 2011 Australian census and the 2013 USA census for only those industry sectors in which the NICTA VRL cohort were employed (Table 15, Figure 9). If the NICTA VRL cohort's industry distribution is similar to that of their discipline peers, then this provides a more valid comparison than that of across all industries.

| | NICTA VRL Cohort | | Australia – 2011 Census | | USA – 2013 ACS | | |
|---|---|---|---|---|---|---|---|
| **ANZSIC 2006 Division** | **Number** | **Percentage of Cohort in Sectors** | **Number** | **Percentage of Doctoral Employees in Sectors** | **NAICS 2012 Sector** | **Number** | **Percentage of Doctoral Employees in Sectors** |
| Manufacturing | 10 | 8.40% | 2970 | 4.03% | Manufacturing | 164918 | 9.80% |
| Information Media & Telecomms | 17 | 14.29% | 1017 | 1.38% | Information Services | 30679 | 1.82% |
| Financial & Insurance Services | 5 | 4.20% | 2102 | 2.85% | Financial Services | 56781 | 3.37% |
| Professional, Scientific & Technical Services | 40 | 33.61% | 16564 | 22.45% | Professional Services | 381998 | 22.70% |
| Administrative and Support Services | 1 | 0.84% | 665 | 0.90% | | | 0.00% |
| Public Administration & Safety | 2 | 0.84% | 8406 | 11.40% | Government & Public Admin/Defence | 118202 | 7.02% |
| Education & Training | 43 | 36.13% | 40870 | 55.40% | Education | 891788 | 53.00% |
| Arts & Recreation Services | 1 | 0.84% | 1175 | 1.59% | Entertainment | 38348 | 2.28% |
| **TOTAL** | **119** | **100%** | **73769** | **100%** | **TOTAL** | **1682714** | **100%** |
| | | Percentage of Total Doctorates | 55% | | Percentage of Total Doctorates | 60% | |

**Table 15: Doctorate Employment by Industry Sector for Sectors Employing NICTA VRL Cohort Members (Data Sources: *Australian Bureau of Statistics, US Census Bureau)***

Considering the Victorian Government preferred outcome of not seeing academia taking up the newly produced PhDs, we can see that in the case of the NICTA VRL cohort this has been achieved, with a far smaller proportion being employed in the Education and Training Sector (36% compared to 55% and 53%). The proportion of the cohort employed in Education is slightly closer to that of PhD graduates from Massachusetts Institute of Technology (MIT) of whom 25% are employed in Education (Massachusetts Institute of Technology, 2015). As could be reasonably expected from a cohort of ICT graduates with enhanced training, the portion of the cohort employed in Information, Media and Telecommunications is ten times that of the census data. Surprisingly, the proportion of employment in Information Services in the US is similar to that of Australia, although there may be differences in the subgroups making up Information Services which contributes to this (Figure 9).

Members of the cohort are more likely to be employed in Manufacturing than other Australian PhDs, and are approaching US levels. As mentioned previously these PhDs are employed in emerging biomedical rather than traditional manufacturing operations.

Members of the NICTA VRL cohort (0.84%) are greatly under-represented in Public Administration and Defence compared to both the Australian (11.4%) and US (7.02%) levels. If the sector distribution of the cohort is representative of their discipline peers, this suggests a serious deficit in technology expertise in Australia's public administration, affecting areas from procurement to policy advice.

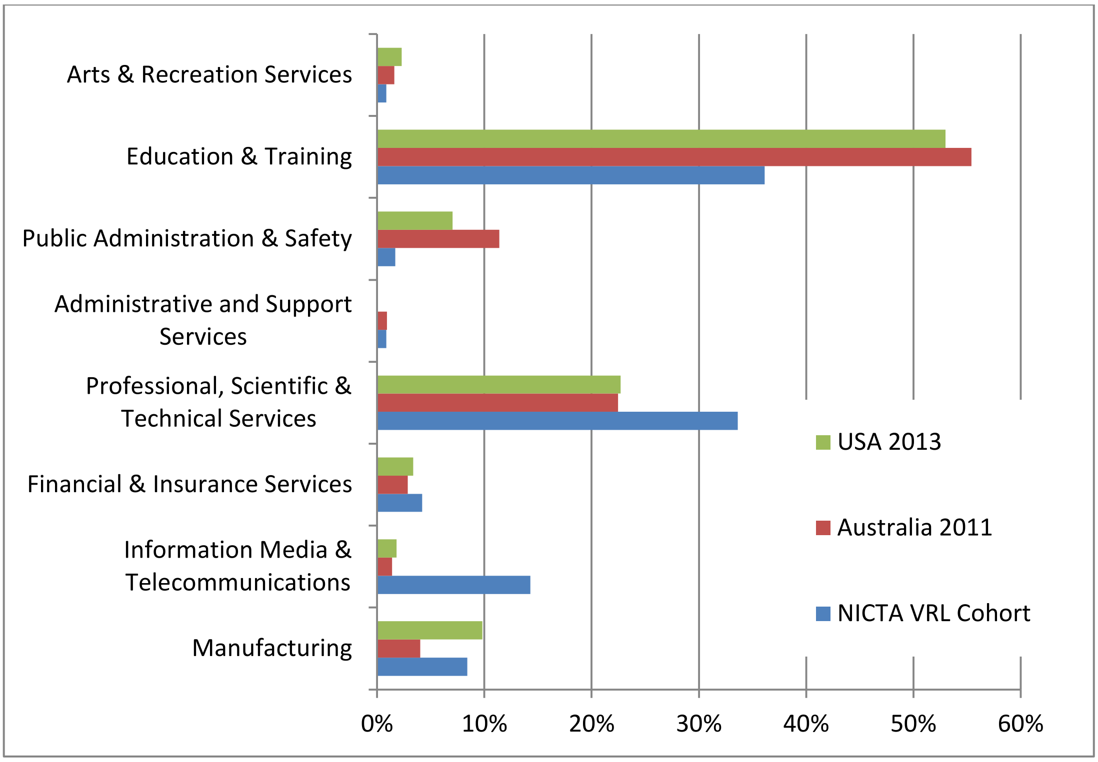


**Figure 9: Distribution of Doctorates across Sectors Employing Members of the NICTA VRL Cohort**

To test the assumption that members of the NICTA VRL cohort are comparable to their discipline peers in regards to industry sector distributions, 2011 Australian Census data was extracted for postgraduate research qualified employment by sectors for individuals who identified their qualification field of study as any of the following at the three digit classification level: information technology, computer science, formal language theory, programming, computational theory, compiler construction, algorithms, data structures, networks and communications, computer graphics, artificial intelligence, computer science, information systems, conceptual modelling, database management, information systems, engineering and related technologies, electrical and electronic engineering, electrical engineering, electronic engineering, computer engineering, communications technologies and biomedical engineering. This resulted in data relating to 10,076 individuals across the country. Those for whom the industry of employment was not stated, inadequately described, or not applicable were removed, leaving a comparison cohort of 8,437 (Table 16).

| Industry Sector | Australia 2011 Census (n = 8,437) | NICTA VRL Cohort (n = 119) |
|---|---|---|
| Agriculture, Forestry and Fishing | 0.26% | 0.00% |
| Mining | 1.62% | 0.00% |
| Manufacturing | 6.57% | 8.40% |
| Electricity, Gas, Water and Waste Services | 2.28% | 0.00% |
| Construction | 1.59% | 0.00% |
| Wholesale Trade | 2.36% | 0.00% |
| Retail Trade | 0.96% | 0.00% |
| Accommodation and Food Services | 0.45% | 0.00% |
| Transport, Postal and Warehousing | 1.55% | 0.00% |
| Information Media and Telecommunications | 2.49% | 14.29% |
| Financial and Insurance Services | 3.20% | 4.20% |
| Rental, Hiring and Real Estate Services | 0.31% | 0.00% |
| Professional, Scientific and Technical Services | 29.51% | 33.61% |
| Administrative and Support Services | 0.62% | 0.84% |
| Public Administration and Safety | 7.21% | 1.68% |
| Education and Training | 36.67% | 36.13% |
| Health Care and Social Assistance | 1.22% | 0.00% |
| Arts and Recreation Services | 0.28% | 0.84% |
| Other Services | 0.85% | 0.00% |
| **TOTAL** | **100%** | **100%** |

**Table 16: RHD Sector Employment for Selected Fields of Study**

Under this comparison, NICTA VRL cohort members are employed across a far smaller range of industry sectors than members of these discipline groups. This will largely be a function of the small size of the cohort, at 1.6% of the census cohort. The data also suggests that, not withstanding the smaller sector range, the NICTA VRL cohort are reasonably representative of their discipline peers in regards to employment in the Education and Training and Professional, Scientific and Technical Services sectors, but very different in their participation in Information Media and Telecommunications (12.69% versus 2.08%) and Public Administration and Safety (1.49% versus 6.03%) (Table 16).

The increased participation in Information Media and Telecommunications by members of the NICTA VRL cohort may be due to a larger proportion of these individuals undertaking their studies in areas such as optical communications than in the census cohort at a time when the National Broadband Network was being initiated. It is reassuring to find that the proportion of Australian research higher degree holders in these areas employed in Public Administration is four times that of the NICTA VRL cohort, although many would argue there is still need for improvement (Table 12).

As members of the NICTA VRL cohort all undertook their studies within the Departments of Computer Science and Software Engineering and Electrical and Electronic Engineering, a comparison was then made with 2011 census data for those who identified their field of study as electrical, electronic or computer engineering (Figure 10). This subset of the larger IT and Engineering disciplines numbered 1,270.

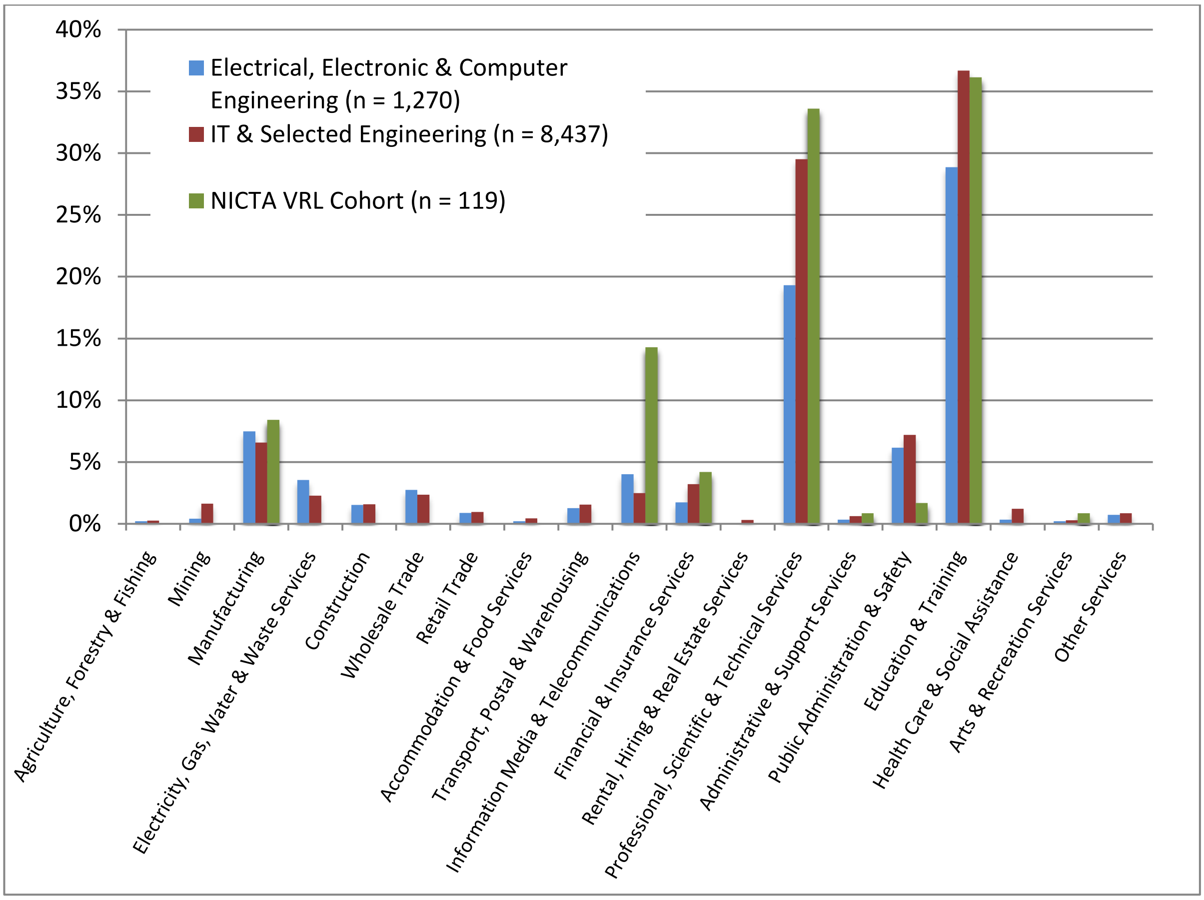


**Figure 10: Industry Sector Employment for Selected Field of Study Subsets and the NICTA VRL Cohort (Data Source: *2011 Census of Population and Households, Australian Bureau of Statistics*)**

For a number of industry sectors research higher degree participation is similar between the two census field of study cohorts. This is unsurprising as the Electrical, Electronic and Computer Engineering cohort is a subset of the larger IT and Selected Engineering cohort. The very low numbers of research higher degree holders in certain sectors makes comparisons in these sectors highly unreliable. There are, however, a small number of sectors where interesting differences emerge.

In the two sectors employing most members of all cohorts – Education and Training and Professional, Scientific and Technical Services - members of the NICTA VRL cohort participate at a rate more similar to that of the wider IT and Engineering cohort than that of their closer discipline peers (Figure 10) and these two sectors also exhibit the largest differences between the census cohorts. Surprisingly, the participation rate by NICTA VRL cohort members in Information Media and Telecommunications is more than three times that of their engineering peers (4% versus 14.3%) and almost six times that of the wider IT and engineering cohort (2.5%). Anecdotal evidence from NICTA VRL students who did not complete their research higher degree suggests that having a doctorate is not necessarily an advantage when working in some sub-sectors of the IT industry. A number of students who were employed by software companies prior to submission of their thesis still had not submitted several years later. Members of the NICTA cohort are far less likely to be employed in Public Administration and Safety.

*Public and Private Sector Employment of Research Higher Degree Holders*

High level sectors used by the OECD in Research & Development Indicators may provide some guidance in regard to public and private sector employment, with Australia having a 'business enterprise' participation rate for researchers of less than 30% (Figure 11). However, while most researchers, as opposed to research technicians, will be doctorate holders, it is not necessarily the case that all will be. Additionally, not all research higher degree holders will be working as researchers, especially in industry. Members of the NICTA cohort are employed in many occupations: consultants, advisors, technicians, analysts, managers.

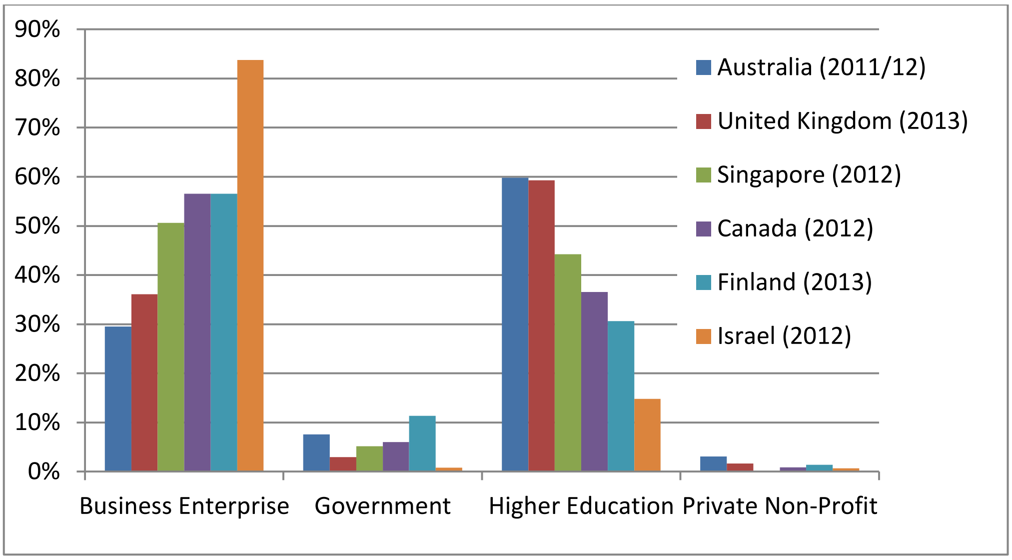


**Figure 11: Researcher Employment across Sectors (Data Source: OECD R-D Personnel by Sector of Employment and Occupation Database)**

Australia's low participation rate for researchers in industry may be reflective of the relatively low level of research and development undertaken within the business enterprise sector rather than a low rate of research higher degree participation in industry overall (Figure 12). This then raises the question of to what extent Australia's level of industry R&D is because of or the cause of a perceived low level of research higher degree participation in industry generally.

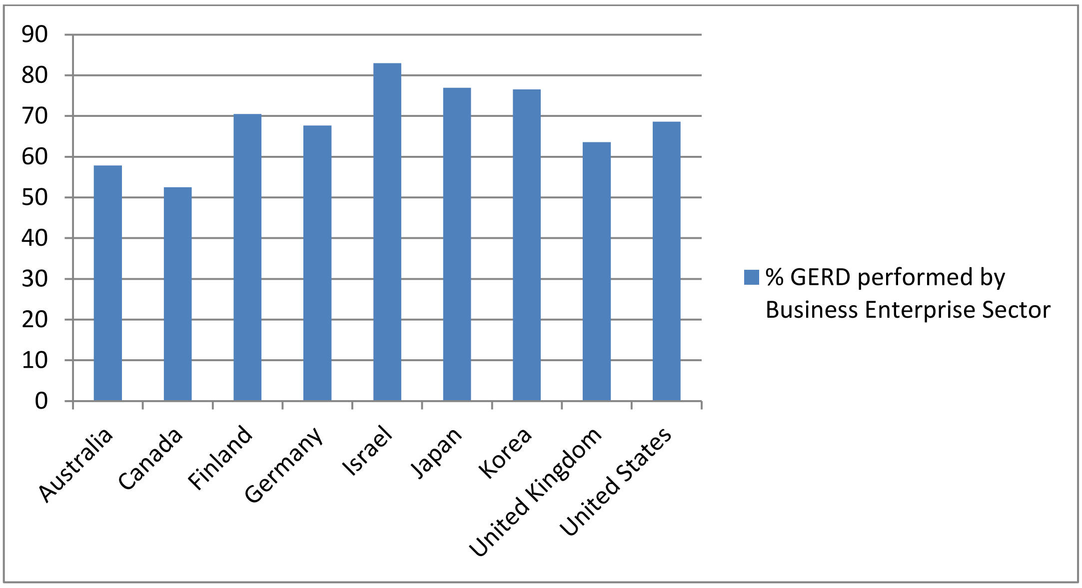


**Figure 12: Percentage of National R&D Performed by the Business Enterprise Sector, 2011 (Data Source: *OECD Main Science & Technology Indicators Database*)**

For the selected IT and Engineering fields of study, private sector employment for research higher degrees in the 2011 Australian census was recorded at 45%, and for public sector employment, 40% across Commonwealth, State and Local Government (Australian Bureau of Statistics, 2011). Some sectors, such as higher education and medicine, have a far higher portion of non-government operators in the USA compared to Australia. And, as mentioned above, census data for the USA includes doctorate holders from all disciplines. Comparison of the NICTA VRL cohort with National Science Foundation National Center for Science and Engineering Statistics postdoctoral survey data suggests that members of the cohort have employment distributions similar to their peers in the USA when it comes to economic entity (Table 17).

| | NICTA Cohort | | USA - NSF – SESTAT | |
|---|---|---|---|---|
| | **Number** | **%** | **Number** | **%** |
| **Higher Education/NFP/Medical Institutions** | 54 | 40% | 330630 | 39% |
| **Business/Industry** | 57 | 43% | 324133 | 39% |
| **Government/PFRA** | 8 | 6% | 66039 | 8% |
| **Unknown/N/A** | 15 | 11% | 117137 | 14% |
| **TOTAL** | **134** | **100%** | **837939** | **100%** |

Table 17: NICTA VRL Cohort and USA Science & Engineering Doctoral Employment by Economic Entity (USA Data Source: *SESTAT 2013*)

Graduate employment surveys are a regular feature of the higher education sector. Within Australia, Graduate Careers Australia administers the *Australian Graduate Survey*, taken four months after course completion, and the *Beyond Graduation Survey*, taken at three years post course completion. The *Australian Graduate Survey* aggregates a number of smaller surveys, including the *Postgraduate Destination Survey.* The 2013 survey indicated that 40.9% of Masters by Research and PhD students who were in full-time employment in the first months following completion were working in the higher education sector (Guthrie & Bryant, 2013) (Table 18). This is also above the 2011 Australian census level of 30% of all PhDs working across the whole education sector (Table 12). Similarly, the private sector participation rate of 25% is well below the 48% participation rate by members of the NICTA VRL cohort (Table 10).

| | Percentage of Masters by Research/PhD Graduates Employed (%) |
|---|---|
| **Government** | 8.0 |
| **Education** | |
| Higher education | 40.9 |
| Other education | 9.6 |
| **Total education** | **50.5** |
| **Health** | 8.9 |
| **Private** | |
| Private practice | 4.7 |
| Other business/industry | 20.1 |
| **Total private** | **24.8** |
| **Other/Not Specified** | 7.9 |

**Table 18: Employment Sector of Full-time Working Graduates, 2013; (n = 2,303) (Data Source: Graduate Careers Australia, *2013 Postgraduate Destinations Table and Figures)***

*Employment of Research Higher Degree Holders Over Time*

The use of initial graduate destination surveys when examining overall research higher degree holder employment in industry may be of limited use. If we look at the first employment destination of members of the NICTA cohort, for 53%, their first jobs were in either in universities or with NICTA itself (Table 19). This is comparable to the estimated 57% of American PhD graduates who take up their first job in academia (Zolas, Goldschlag, Jarmin, Stephan, Owen-Smith, Rosen, McFadden Allen, Weinberg & Lane, 2015). When considering their most recent employer, while the proportion employed in universities had hardly changed, most of those employed by NICTA had moved on to other entities, particularly multinational corporations and start-ups. It does need to be noted that given the wide variations in time since completion for cohort members, a number of those whose first destination is also their most recent destination will have been in the workforce for less than twelve months. However, it does also suggest that within a short period of entering ongoing employment, members of the NICTA cohort were exhibiting similar employment distributions across academia, industry and government to that demonstrated by their American counterparts on entering the workforce (Zolas et al, 2015).

| | First Employment Destination | | Most Recent Employment Destination | |
|---|---|---|---|---|
| **Employer Economic Entity** | **Number** | **%** | **Number** | **%** |
| University | 45 | 38% | 44 | 37% |
| Start-up | 3 | 3% | 10 | 8% |
| SME | 17 | 14% | 21 | 18% |
| MNC | 17 | 14% | 26 | 22% |
| PFRA | 4 | 3% | 4 | 3% |
| NFP | 8 | 7% | 6 | 5% |
| Government | 2 | 2% | 4 | 3% |
| NICTA (NFP) | 23 | 19% | 4 | 3% |
| **TOTAL** | **119** | **100%** | **119** | **100%** |

Table 19: First and Most Recent Employer Economic Entity for NICTA VRL Cohort Members

For those who work in the higher education sector, it will not come as a surprise that for a large number of research higher degree graduates their first employment is with the organisation where they undertook their study. In many instances, supervisors will appoint a new graduate for a short period to continue contributing to a larger research program or to contribute to a research grant. What may not be so obvious is the extent to which these graduates then move on to other sectors. While there is evidence from the NICTA VRL cohort of flows in all directions across sectors, seven times as many have moved from academia or not-for-profit to private industry at some stage than the other way.

For the NICTA VRL cohort the large range of time periods since graduation has resulted in highly varied employment experiences, as one would also expect from any diverse group. Some members of the cohort have spent their post-research higher degree career with a single employer, while others have been very mobile within the workforce. While no firm conclusions can be drawn, the trajectories of some individuals may be instructive as to ways in which research higher degree holders bring benefits to employers through the experience and networks they develop.

Examples of NICTA VRL cohort sector employment mobility include:

- From university to government to university to industry to university to start-up
- From not-for-profit to start-up
- From university to local SME to overseas multi-national

- From university to overseas publicly funded research agency to local multi-national
- From not-for-profit to university to local multi-national corporation
- From government to industry

Traditionally, tracking graduate employment outcomes has relied on surveys, usually within the first twelve months of graduation. The *Australian Graduate Survey* achieves an annual response rate of between 60% and 65% (Graduate Careers Australia, 2015) and one would expect that the further away one gets in time from graduation, the lower response rates will be. The emergence of career and employment-focused social media has the potential to expand and simplify our ability to undertake longitudinal studies to complement current studies on the impact and benefits of higher education to both individuals and societies.

*Conclusions*

Members of the NICTA VRL cohort effectively only have one characteristic in common – that of undertaking a research higher degree at the University of Melbourne with stipend support provided by NICTA VRL. The amount of stipend support provided varied, as did the enrolling Department, the time elapsed since completion and many aspects of the study experience. A relatively small group has then experienced a variety of employment trajectories following completion.

Observations regarding this small and diverse cohort's employment participation cannot lead us to firm conclusions regarding government investment in ICT research higher degree training or the type of training offered. But it may prompt questions that are only now becoming possible to address, thanks to emerging social media networks.

The NICTA VRL cohort does suggest that targeting government funding to support research higher degree training in desired areas promotes capability development. The State of Victoria obtained a 70% increase in highly qualified ICT specialists compared to the number of local students supported. This is largely due to a considerable proportion of international students electing to stay in the state following graduation. NICTA VRL's ability to attract international postgraduate students was assisted by the University of Melbourne's decision to allocate a number of international fee-remission scholarships specifically to students who were receiving stipend support from NICTA. As there is no control group to compare with we cannot definitively say that being in receipt of additional financial support is a determining factor as to whether students elect to remain somewhere after graduation. The prospect of that support may influence the decision as to where a student decides to study such that support for research higher degree students increases the attraction of a region when competing for skilled individuals internationally.

Of course, not all students supported in this way will spend their working life within Victoria. The research higher degree population can be highly mobile, especially those working in the higher education and research sectors. This international mobility promotes trade, cultural and collaborative links.

Observations regarding the NICTA VRL cohort are inconclusive regarding the result of the Government programs involved in increasing the participation rate of research higher degree holders in industry. Generally, members of the NICTA VRL cohort were employed in a similar pattern to their discipline peers. The notable exceptions to this were the sectors of Information Media and Telecommunications and Professional Scientific and Technical Services. Over the time period that the cohort were graduating, IBM Research established a laboratory in Melbourne (IBM, 2011) and the Commonwealth Government initiated the $18.2 billion National Broadband Network (Parliament of Australia, 2011), headquartered in Melbourne. With a number of graduates taking up employment with these organisations this has obviously contributed to the increased participation rates in these two areas, providing increased opportunities for research higher degree holders to be employed by industry within Victoria. What is unknown is the degree to which the presence of a relatively large pipeline of skilled research higher degree graduates influenced the decision to locate in Victoria.

Factors influencing employment of research higher degree holders within particular sectors are many and varied, both on the supply and demand sides. It is easier for governments to influence supply by providing support for students while undertaking their studies and providing pathways to working rights for international students. Demand is harder to influence. As a general rule, policies encouraging high-tech industry and research investment should help to provide more opportunities for research higher degree holders to utilise their skills outside of the academic sphere.

## 7.5 Software and Datasets

In recent decades, research outputs such as software and datasets have increased in importance. Software can be developed in to a consumer product, incorporated in devices, released to the research community for free academic use or provided to the research funder for in-house use. Researchers are encouraged to lodge data sets with repositories to promote re-use and consolidation of data that has often required considerable time and resources to collect. Initiatives such as the *Australian GovHack* are encouraging people to use the increasing amount of open government data in innovative ways.

For software or data sets which incur a fee to use or are formally licenced, it is relatively easy to collect proxy data about their use – through income generated or licences issued. But for academic use, licences may be institutional, covering multitudes of users, or may not be required at all. In these situations it may be harder to see their impact. Software used in scientific research is often built using components that have come from elsewhere, obscuring the contributions made by each component (Howison, Deelman, McLennan, da Silva & Herbsleb, 2015). Open source software may require a licence, or at the very least downloads, which can usually be tracked easily. However, as noted by Howison et al (2015),

> *"… , distribution is a poor proxy for use. Many downloads may not result in use … downloads may result from … bot downloads. … when software is updated …. Actual users may re-download the software."*

These are essentially the same issues as we face when attempting to correlate publication downloads with eventual citations and impact. Embedded software is licenced to manufacturers, not end users, in which case the number of units sold containing the software becomes important. These sorts of metrics tend to focus on the economic impact, but further details can provide insights to other forms of impact. For example, the environmental impact of a piece of embedded software that reduces carbon monoxide emissions from car engines can be inferred from the market share held by manufacturers incorporating the software. Concepts such as 'software mileage' (a measure of new customers gained for every line of code that is written) have been proposed to assist in comparing the impact of software across sectors which vary significantly in volume and value (van Genuchten & Hatton, 2013). It must be kept in mind that this sort of data may be difficult for assessors to access due to commercial reasons.

Unlike journal articles and conference papers, consensus regarding how to acknowledge the use of software and datasets in research is still developing. They may be formally cited as a reference, mentioned in the body of the article (usually as part of the method), the provider named in the acknowledgements, or not referred to at all. Pan, Yan, Wang and Hua (2015) found that almost 80% of articles published in PLoS ONE during a single year mentioned software, with a relatively low portion of the software packages mentioned (40%) receiving actual citations, indicating a large degree of formal under-citation. Similarly, Howison and Bullard's (2015) study of biology publications found that while 65% of publications mentioned software, only 44% of these were actually included within the reference list.

Datasets are an output which may have impact both in terms of the research they were originally collected for, or in their re-use and integration with other sets. This can accelerate the time or reduce the costs for future research outcomes. Datasets also provide a valuable asset for use in decision making when interrogated appropriately. Analysis of datasets recorded in the Thompson Reuters *Data Citation Index* suggests that under-citation also occurs for this class of output, and citation of the repository often replaces that of the actual dataset (Belter, 2014; Peters, Kraker, Lex, Gumpenberger & Gorraiz, 2015; Peters, Kraker, Lex, Gumpenberger & Gorraiz, 2016).

If the contribution of these important research outputs is under-represented in the corpus which we traditionally use to determine research outputs, productivity and excellence, then it would not be unrealistic to expect that the same will occur when we attempt to assess wider impact.

## 7.6 Diffusion, Influence & the Intangibles

*"The objective of all forms of public engagement and communication is to expand the circulation of new information on topics that are studied … and are of interest to a wide range of constituencies."*

– American Sociological Association, What Counts? Evaluating Public Communication in Tenure and Promotion, 2016

For research to have any impact it must be communicated to the audience of potential users. Within the academic community this is achieved via the traditional dissemination channels of journal publishing and conference presentations. The diffusion of ideas via informal means or what has sometimes been termed 'Coffee House Culture' after the contribution of coffee houses to the 17th and 18th century explosion of innovation (Johnson, 2010; The Economist, 2003) plays a vital role in promoting collaboration and spreading ideas to industry. Yet it is extremely difficult to trace the precedents of a research outcome through this largely undocumented trail. But if we are talking about potential for impact then it should be self-evident that the more opportunities there are for people to be exposed to ideas and collaborators then the greater the potential.

### *7.6.1 Altmetrics*

Altmetrics have emerged in recent years, principally as a way of attempting to quantify the impact of a research output outside the traditional citation environment. In broad terms, altmetrics appear to fall in to one of two main categories:

1. Those that measure "discussion" or "awareness" via social media and non-academic venues (for example: mentions and hyperlinks via Facebook, Twitter, blogs, general news sites, Reddit, Google+).

2. Those that measure "use" of research publications that may not result in citation in other research papers (for example: article downloads, page reads).

The development of useful altmetrics has become possible thanks to the ways in which the internet has allowed researchers, publishers and individuals to share new knowledge. In addition to research articles, altmetrics can be used to monitor other research outputs such as data sets, white papers, public events; and can be used to involve the community in research while it is actually underway. The *Becker Medical Library Model for Assessment of Research Impact Model*[20] suggests social media outputs be used as an indicator for research outputs and activities.

Many academic publishers now include selected altmetrics alongside the citation data for individual papers. For example, PLoS ONE includes alongside each paper real-time counts of views, saves and shares alongside the traditional citations[21]. A number of commercial entities provide tools to allow researchers and institutions to track altmetrics. Browser plug-ins like *Altmetric It*[22] allow any web user to gain detailed altmetrics about almost any published article with a digital object identifier (DOI). Elsevier have recently incorporated downloads and view data from *ScienceDirect* and *Scopus* in their *SciVal* research analysis

---

[20] https://becker.wustl.edu/impact-assessment accessed 1st September 2015
[21] As an example, see http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0133361 accessed 1st September 2015
[22] http://www.altmetric.com/bookmarklet.php accessed 1st September 2015

tool[23]. In addition to these article level altmetrics, services such as *ImpactStory*[24] and *Plum Analytics*[25] aggregate altmetric and traditional citation indicators to provide an overall picture of an individual's impact based on articles (see Melero, 2015, for a listing of data sources for the main aggregation services).

There is some evidence there can be an association of varying strengths between certain altmetrics such as Twitter, Facebook, blogs, forums and mainstream media and eventual citation counts, at least in particular disciplines (Shuai, Pepe & Bollen, 2012; Thewall, Haustein, Larviere & Sugimoto, 2013; Shema, Bar-Ilan & Thelwall, 2014; Costas, Zahedi & Wouters, 2015; Ringelhan, Wollersheim & Welpe, 2015). Given that papers with higher visibility and easier access tend to be cited more (for example: Ebrahim, Salehi, Embi, Tanha, Gholizadeh & Motahar, 2014; Dietrich, 2008; Eysenbach, 2006; Aksnes, 2003; Peritz, 1995) it may be the referencing to a particular paper in these altmetrics increases visibility and contributes to increased citation. If this is the case, being more citable does not drive higher altmetric indicators, rather higher altmetric indicators are helping a paper to become more citable. Is the correlation actually causation? This circular relationship may be the underlying reason for the variations in the association between individual altmetrics and citation rates. Increased visibility arising from social media for example, will only help the citation counts of those papers that actually deserve it.

Traditionally, visibility was largely a function of the circulation and reputation of the journal a paper was published in (as often demonstrated by impact factor). But just because a paper is published in a high impact journal it is no guarantee of citations – the work must also deserve them. Now, visibility is also driven by factors such as news releases, Twitter feeds, blog mentions and search engine optimisation, but one thing remains unchanged. A paper must earn its citations through the quality, relevance and utility of the work being reported.

[23] http://www.elsevier.com/solutions/scival/features/scival-trends-module accessed 1st September 2015
[24] https://impactstory.org/ accessed 1st September 2015
[25] http://plumanalytics.com/products/plumx-metrics/ accessed 1st September 2015

While a correlation between altmetrics and citation may be useful for the early identification of influential papers, some altmetrics may ultimately be more useful as an indicator of wider information diffusion.  As suggested by Bornmann (2015a), social media altmetrics such as Twitter and Facebook may provide us with an indication of work which is of interest to those outside of the relatively small circle of peers publishing research in your area of speciality. However, we must keep in mind Thelwall and Kousha's (2015) assertion that there have not been any studies that have found evidence of a substantial Twitter audience for academic research outside of the academic community itself.  From this, they infer that Twitter mentions will most likely not prove to be useful when undertaking impact evaluations (Thelwall & Kousha, 2015a).

Wikipedia citations are an interesting altmetric.  For a journal article to be referenced by Wikipedia and its ilk is

> *"… akin to making it into a textbook about the subject area and being read by a much wider audience that goes beyond the scientific community."* (Fenner, 2013).

Yet, similar to the lack of attention given to textbooks in traditional bibliometrics, discussions of altmetrics often exclude Wikipedia.  Given that Wikipedia is often the first port of call for those seeking information, research which informs its articles will be exposed to a significant audience that traditionally has been ignored.  In terms of impact reach, research that is cited in Wikipedia will receive a significant boost.

Analysis of *Scopus* data by Ioannidis, Boyack and Klavans (2014) suggests only 1% of the scientific workforce have a consistent publishing record over a period of 16 years.   Brizan, Gallagher, Jahangir and Brown (2016) report that for six million publications between 1950 and 2008, more than 70% of identified authors were represented by only one paper, yet presumably many of these authors will have continued to read and use research literature.  There is a general acknowledgement there is a large portion of the scientific workforce that do not publish at all, especially once they have completed their studies. Many who work in private industry may not publish but may use the scientific literature to inform their work. Clinicians may have their practice informed by the literature. Papers which provide clear overviews and are considered good teaching resources may have a wider impact without necessarily showing up in the citation literature, but may be captured as part of altmetrics (Bornmann & Haunschild, 2015).

In addition to those who are considered to be 'citation silent', publishing researchers may also read and be influenced by many papers that do not end up being cited (Florence, 2015). This is particularly the case early in careers or when moving in to new fields of research. Indeed, analysis of the (self-identified) category of registered *Mendeley* users found that within all disciplines, the majority of readers were PhD students (Mohammadi, Thelwall, Haustein & Larivière, 2015). Mohammadi et al (2015) do note there are a number of possible reasons for why students are the heaviest users of *Mendeley*, including increased adaptation to new technologies. Nonetheless, the preparation of this thesis is a typical example of non-cited influence: the number of papers read as background is much greater than those that have been directly referenced but all will have influenced the direction of the work. Moed (2005a) suggests

> *"… the number of downloads primarily reflects a community's awareness of a paper, in terms of its availability and particularly its face value. … downloads and citations relate to distinct phases in the process of collecting and processing relevant scientific information that eventually leads to the publication of a journal article, the former being located more in the beginning, and the latter more towards the end of it."*

While downloads and views provide an indication of the wider reach of a paper, they are no guarantee the work has actually been read. There is no simple way of knowing the reason for access: it may be researchers or groups collating their publications. As Mohammadi et al (2015) note there is more research needed to be done on why *Mendeley* users actually register articles in their library so that it can be determined how often registration means that document is actually read. This will still not give us the full story - even when a paper has been read, it may be discarded as being irrelevant.

Using *Science Direct* data across the disciplines of economics, arts and humanities, oncology and computer science, Gorraiz, Gumpenberger and Schlögl (2014) found that more than 90% of the publications generated between 2002 and 2011 were downloaded at least once in 2011. They calculate that, depending on the discipline, there are between 50 and 140 downloads of a publication for each eventual citation. Public Library of Science (PLoS) suggests for each citation received by a PLoS journal article there are 300 online article views (Fenner, 2013), while only one in seventy document downloads will be cited (Lin & Fenner, 2013). This suggests 'citation silent' use (whether in terms of the user or the purpose) may be the norm in some disciplines.

Not withstanding the large numbers of document downloads which do not lead to citations, there have been some reports of a positive correlation between download numbers and eventual citations (for example: O'Leary, 2008; Schlögl, Gorraiz, Gumpenberger, Jack & Kraker, 2014; Moed & Halevi, 2016), although it has been suggested this may be due to citations being a good indicator of downloads rather than downloads being a good indicator of citations (Kurtz, Eichhorn, Accomazzi, Grant, Demleitner, Murray, Martimbeau & Elwall, 2005). This correlation is not a universal finding with a number of studies alternately finding high downloads do not equate to increased citation (for example: Nieder, Dalhaug & Aandahl, 2013; Bazrafshan, Akbar Haghdoost & Zare, 2015). Similarly, there may be a correlation between readership and bookmarking of publications in on-line reference managers such as *Mendeley* and traditional citation (Li, Thelwall & Giustini, 2012; Bornmann, 2015; Shrivastava & Mahajan, 2016; Maflahi & Thelwall, 2016), but if this is the case, then these altmetrics do not tell us much that is new compared to what we already know from traditional citation analysis. The main benefits of these download and readership metrics are likely to be in the earlier identification of highly-cited papers and in providing a sense of the size of the non-citing readership.

There have also been suggestions the *ResearchGate Score* calculated by the academic social networking site *ResearchGate* correlates with *Scopus* and *SciVal* indicators such as field-weighted citation-impact (Shrivastava, 2015; Yu, Wu, Alhalabi, Kao & Wu, 2016) and as such could be useful for both individual and institutional comparisons. The *ResearchGate Score* suffers from the general deficiencies of composite scores as identified by Gingras (2014), with no transparency as to how the score is arrived at. Hoffman, Lutz and Meckel (2016) were surprised to find that the *ResearchGate Score* has a significant negative impact on the network centrality of users (which one would expect to correlate with influence and impact), and in the absence of information regarding how the score is obtained were unable to suggest any possible explanations. In addition, as noted by Chin Roemer and Borchardt (2015), social media users are more likely to be younger and

> *"… public social media metrics are likely to be more relevant to fields with compatible communication habits, methods, or researcher demographics…".*

While Roemer and Borchardt (2015) were referring mainly to applications such as Twitter, Instagram, and Facebook, these observations are also likely to hold for research-focused social media. In their study of a Swiss cohort, Hoffmann et al (2016) found junior members of faculty tend to be more active in their *ResearchGate* community than senior members. It has also been noted there are significant differences in the proportion of researchers using *ResearchGate* across different countries (Thelwall & Kousha, 2015), further making comparison difficult within the global research sector. As a composite score with user demographics that will vary according to factors such as discipline and country of work, the use of *ResearchGate Score* as a comparator would appear to be problematic at the very least. Many indicators only provide useful information if there is a standard that can be referred to and in this case, an indicator which can suggest you are in the top percentile of your peers could be misleading when the size of the sample is unknown.

In applying social network analysis to *ResearchGate,* Hoffmann et al (2016) found the online network participants were members of largely reflected their offline networks and

> *"… relational measures derived from interactions on an academic SNS are related to more traditional measures of scientific impact. However, they also exhibit some notable platform-specific dynamics:…"*

This suggests information derived from *ResearchGate* data and networks is likely to be complementary to that derived from traditional data sources and bibliometric analysis.

It has been suggested altmetrics may be a future alternative to current peer review methods. With peer-review being crowd-sourced, instead of waiting several months to receive two or three opinions on a paper, it might be assessed by thousands of readers within a week (Priem, Taraborelli, Groth & Neylon, 2010). However, just as we now recognise the potential for manipulating traditional peer review and bibliometrics, so too has the potential for exploitation of altmetrics started to become apparent through practices such as the trade in fake Twitter followers. Chin Roemer and Borchardt (2015) consider this to be a relatively low risk given that perpetrators are likely to be the same small group that are already attempting to game citation and impact factor and the ongoing improvements in the ability to detect spambots and the like.

Taylor (2013) suggests altmetrics may provide a starting point for those searching for metrics to complement approaches such as case studies and citations when assessing social impact. He is careful to point out that significant work is required before altmetrics can be considered as robust an indicator as traditional bibliometric indicators. Thelwall, Kousha, Dinsmore and Dolby (2016) suggest some altmetrics show promise for use in the evaluation of research funding programs (for example, F1000 scores for biomedical science, Google Books citations for humanities and *Mendeley* readers for recently published articles) but caution they must be collected and interpreted with care, such that

*"… the results are unlikely to give clear-cut conclusions. Nevertheless, these indicators may be useful for early impact evidence or to reflect alternative types of impact, …, but should be used to inform human judgements rather than to replace them. … it can perhaps be taken as a starting point for discussion but should not drive conclusions."*

Waltman and Costas (2014) found while there is a correlation between F1000 recommendation and eventual citations it is actually weaker than that between citations and indicators such as journal impact factor. As noted by Bornmann (2015b), studies to date have come to differing conclusions regarding F1000 recommendations and citation prediction, so Thelwall et al's (2016) caution is well founded.

When using altmetrics in relation to impact it is also important to remember that many of them do not actually tell us anything about impact, not even social impact, but rather, are an indicator of *social reach* – the extent to which research findings move from the formal literature into the wider public domain (Taylor, 2013). Taylor (2013) further describes this as altmetrics providing

*"… a way of detecting when research is being passed on down the information chains – to be specific, altmetrics detects sharing, or propagation events."*

Sometimes this is phrased as the potential of altmetrics for measuring research consumption (Barnes, 2015), but as noted above, it is difficult to determine any information regarding how that research is being consumed and used.

Major altmetric provider Altmetrics themselves remind users their *Altmetric Score* measures attention and makes no claims concerning the quality of an article (Adie, 2013). While we also recognise that controversial research papers may receive many citations as they are rebutted, it would be apparent to most observers that the level of social media activity is not always a reflection of that which is judged to be of value. The *Altmetric Score* is also a composite score, and while *Altmetric* do provide information about the factors which are considered and the relative weightings of some data sources, like the

*ResearchGate Score* it fails the Gingras (2014) criteria for appropriate indicators. As eloquently expressed by Trueger, Thoma, Hsu, Sullivan, Peters and Lin (2015):

> *"The exclusion of traditional journal citations from Altmetric scores is a limitation to its validity as a metric of scholarly impact, especially in the academic community. However, altmetrics' ability to measure disseminative impact quickly and the correlation with citations suggest that altmetrics may serve as a useful complement to journal impact factor."*

Given the issues associated with journal impact factor, *Altmetric Scores* should be used as a complement to a range of traditional bibliometric indicators and evaluation methods.

When considering using altmetrics, particularly those associated with social media activity and public writing, we must keep in mind the sometimes brutal nature of the social media landscape and how it may influence individual's choices regarding both engagement with the medium and a willingness to conduct research in controversial topic areas. Abuse and harassment via Twitter, Facebook or article comments can be personal and threatening, rather than focused on debating ideas or challenging arguments (for example, Hardaker & McGlashan, 2016; Al-garadi, Varathan & Ravana, 2016). There are suggestions that disproportionally the victims of such behaviour are singled out due to their gender, race, sexuality, religion or ethnicity (for example, Gardiner, Mansfield, Anderson, Holder, Louter & Ulmanu, 2016; Pew Research Centre, 2014). This in turn raises concerns that a wish to avoid this type of response leads to self-censorship and unwillingness to participate, stifling academic debate, freedom of expression and perpetuating the orthodoxy of contributing voices (Bernstein, 2014; American Sociological Association, 2016). An understandable reluctance to expose oneself to the more confronting examples of internet behaviour has the potential to disadvantage researchers who may be members of minority groups when being assessed in regards to public engagement.

The limitations of social media metrics as a whole and issues regarding online behaviour does not mean case study analysis of social media activity for individual papers cannot be illuminating. Dinsmore, Allen and Dolby (2014) cite the example of a Wellcome Trust paper examining industry submissions to a government policy consultation. The paper was uncited for the first three months following publication, but was tweeted four times as often as the journal average and seventy times as often as other Wellcome Trust papers across the publisher's suite of journals. Further analysis showed that key influencers, including members of the European Parliament and international non-governmental organisations, were among those tweeting, suggesting that research with an apparently local focus was having a global influence (Dinsmore et al, 2014). In this instance, it is clear that both the quantity and quality of social media activity are demonstrating potential influence and impact. This will not always be the case, but such data will provide an indication of interest in the non-citing community.

Haustein, Costas and Larivière (2015) report 21.5% of academic papers are the subject of at least one tweet, while less than 5% are shared on Facebook, compared to 66.8% of papers receiving at least one citation. Higher numbers of references and greater collaborations are associated with increases in both citations and social media mentions. But, in other aspects, the two platforms act differently – longer papers have more citations, while shorter papers have more social media. Editorials and news articles tend not to be cited, but they are more often tweeted. Humanities and social science papers are more common on social media, yet are cited less than those in the traditional sciences (Haustein et al, 2015). From this Haustein et al (2015) conclude social media mentions and citation rates are driven by different factors, so that, at best, social media metrics complement other types of indicators. This accords with the notion that a range of indicators are needed to be considered within context when considering impact.

Existing, as it does, outside the traditional citation environment, grey literature is one area where certain altmetrics may be able to provide us with new information regarding impact. Wilkinson, Sud and Thelwall (2014) have proposed the web impact report, or *WIRe*, as a method of assessing the impact of grey literature that is distributed via the web. As the grey literature is aimed at non-academic users, this analysis of web page mentions has the potential to provide valuable information about the context in which grey literature is mention on the web. But as Wilkinson et al (2014) themselves note, the information returned has to be interpreted in regards to its value.

### *7.6.2 Influence*

In some ways influence and impact can appear to be interchangeable – the findings from research on the effects of tobacco smoking on health have influenced both policy and individual responses, leading to public health impacts. Influence may also be more closely associated with individuals undertaking research rather than the actual piece of research itself. In this situation the research becomes one of the methods by which an individual builds credibility as well as exerting influence. Marketing and advertising are often reliant on consumers being influenced more by the messenger rather than the message. Why else would movie stars be used to sell cars and coffee?

How then do we measure influence? Many altmetrics will provide an indication of potential influence for both the individual researcher (for example, the number of twitter followers) and for a piece of research (for example, the number of retweets). The *Klout Score*[26] combines data from sources such as Twitter, Facebook, Wikipedia, Instagram, Bing and Linked-In to provide an influence score out of 100. This is achieved by combining activity and reaction measures (for example, postings and their likes, tweets and their retweets) with information about who is providing the reaction (for example, number of followers) to provide a measure of influence. Other providers of integrated *social influence* indicators include PeerIndex/Brandwatch[27] and Kred[28].

*Klout Score* is based on admirable concepts, including

- Influence is the ability to drive action; and

[26] https://klout.com/corp/score, accessed 8 September 2015
[27] https://www.brandwatch.com/peerindex-and-brandwatch/ , accessed 8 September 2015
[28] http://www.go.kred/ , accessed 8 September 2015

- Being active is different to being influential.

The operating definition of influence used by Klout includes

> *"When you share something on social media in real life and people respond, that's influence"*[29].

While that is inherently correct, there are gradations of action and response. Klout's business is focused on online and social media impact, so for them the action or response being driven is within the social media environment. When a Facebook post highlighting new health research prompts someone to visit their doctor, the influence is quite different to when someone responds by liking or re-posting it. This is the essential problem for many metrics relating to impact and influence. They are indicative of potential rather than reliable for actual and it is difficult to distinguish high from low impact responses by an individual.

Academic genealogy is the practice of building family trees of influence within the academic community. A time consuming enterprise, the practice has been used to examine individuals (for example, Kobayashi, 2015) and discipline groups (for example, Russell & Sugimoto, 2009; Chang, 2010). Russell and Sugimoto (2009) developed the MPACT scoring system to generate a family tree in library and information science and to then rank individuals within the tree based on their influence on the discipline. MPACT is based largely on involvement in doctoral training as either dissertation advisors/supervisors or committee members, producing a comparable metric. Russell and Sugimoto (2009) found that it is actually uncommon for advisors/supervisors to mentor students who then go on to become advisors or supervisors. This should not be a surprise given that most doctoral students find employment outside of academia.

This finding in itself demonstrates one of the limitations of using this approach to study influence – the influence being studied is largely confined to the academic community. As discussed in Chapter 3.3 research's greatest impact is likely to be in the training of research higher degree students who then take the

[29] https://klout.com/corp/score, accessed 8 September 2015

skills and approaches they have developed outside the academy. Influential alumni are a cornerstone of university reputations and social media now supplies many tools for tracking alumni.

Influence within the academic community can also be tracked via acknowledgement counts. The types of acknowledgements included in research publications can vary widely: access to equipment or facilities, technical assistance, commenting on the manuscript, data or sample provision.

A particular form of acknowledgement count focuses on funding acknowledgement. In the late 1990's and early 2000's a link was noticed between the number of funding bodies acknowledged, the reputation of the funding bodies and the citation impact of papers (Lewison & Dawson, 1998; Lewison & Devey, 1999; Boyack, 2004). Lewison and Dawson (1998) suggest this correlation may reflect the application having been through more than one peer review screening process. Thus the more funding sources, the higher the number of peers that have judged the work as being worthy of funding.

Recent analysis has confirmed this correlation may exist, with reservations. Wang and Shapira (2015) found that for 89,000 nanotechnology publications recorded in *World of Science,* those that included grant funding acknowledgements were both published in journals with higher impact factors and received more citations over the studied time period. Rigby (2013), using a smaller sample of 3,596 papers from a single journal (Journal of Biological Chemistry) found that the link between the number of funding sources acknowledged in a single paper and the resultant citation impact was statistically significant, but weak. This is in accord with similar results found for papers published in Physical Review Letters during 2009, while no such relationship was found for papers published in Cell (Rigby, 2011).

From these analyses it could be inferred that any correlation between the number of funding acknowledgements and citation impact may be dependent on discipline. While this may certainly be the case, it may also be that sample size and time frame for citation analysis also heavily influence the correlation. Paul-Hus, Desrochers and Costas (2016) found the indexing of funding acknowledgement data is inconsistent across time, indexes, language and publication type, suggesting bibliometric analysis may not be reliable.

Funding acknowledgements are often imprecise, but even if the correlation between the number of funding sources and citation impact is real, it will not necessarily provide us with any more insight to the potential impact of a piece of research outside the academy. If the acknowledgement includes the funding program as well as the funding agency, it may prove to be useful for determining the success of programs in achieving certain goals: for example, Wang and Shapiro's (2015) analysis suggests joint solicitations for proposals do increase rates of collaboration.

Another area where individual researchers may exert influence is through their involvement in expert bodies such as advisory panels, working groups, standards and practice committees and reference groups. Indeed, for many researchers this may be their primary mode of influencing society. Here though, the opportunity to have influence is usually predicated on a body of work that has contributed to the reputation of the researcher, rather than a single piece of research. In this situation, one can say that all research an individual has undertaken to date has contributed towards the impacts that arise from the outputs of that expert body.

Pontis and Blandford (2016) suggest academics draw on five categories of indicators when attempting to determine who might be influential in a particular area:

- Professional expertise (for example: publications, conferences, membership of research groups, citation counts);
- Domain expertise (for example: seminal work or contributions to the domain);
- Education (universities attended, year of graduation);
- Research community (for example: peer recognition, awards); *and*

- Personal relationship (for example: has the academic heard of or worked with them).

Individuals will place different weights on a mix of quantitative and qualitative information in order to arise at what is effectively a value judgement – similar to what is required when assessing research impact. The ways in which these weightings can vary has been demonstrated by Derrick, Haynes, Chapman and Hall's (2011) study comparing bibliometric indices and peer standing across a number of public health fields in Australia. While finding that for most fields there is a positive correlation between indices and reputation, for researchers in the area of tobacco health there is a poor correlation. Derrick et al (2011) attributes this to a situation where

> *"… Australian tobacco researchers primarily evaluate influence by their impacts on government policy rather than solely rely on publishing in peer reviewed literature"*

arising from Australia's comprehensive tobacco control policies and sustained falls in use over recent decades. In this situation, bibliometric analysis would be a poor indicator of influence or impact.

### *7.6.3 Outreach and Engagement*

The expectations policy makers have concerning the movement of knowledge and technology from universities into industry where they will result in innovations leading to economic impacts has been characterised as often being naive (Gertner, Roberts & Charles, 2011). Attention tends to be focused on the transfer of knowledge via formal or codified means such as patents and contract research. This is understandable, after all, these are activities that are relatively easy to observe and measure.

Informal transfer of knowledge from universities to industry, whether through informal contacts or conferences, exposes companies to technological advances without having to commit substantial resources; provides tacit knowledge which may be necessary for full technological exploitation and facilitates recruitment (Grimpe & Hussinger, 2013). Grimpe and Hussinger's (2013) study of more than 2,000 German manufacturing companies found companies which engage in both informal and formal engagement with universities have a higher level of successful technology transfer than those in which only one mechanism is employed. They suggest

> *"Firms interested in setting up a relationship with a university to transfer knowledge and technology should be aware that the full potential of such a transfer can only be realized if both transfer channels are used."* (Grimpe & Hussinger, 2013).

This is because companies not only require the knowledge codified in formal transfers such as patents, but also need the tacit knowledge that surrounds it. As such, long term relationships with varying degrees of formality and informality are best (Grimpe & Hussinger, 2013).

Providing opportunities for the public, industry and research to interact, exchange ideas and form networks may be even more important for encouraging innovation in service industries. Koch and Strotmann (2008) report that while access to university and research institute generated knowledge positively influences radical innovation in these companies, having a formal co-operative relationship does not increase the likelihood of it occurring.

Given that it can be difficult for industry, particularly SMEs, to formally engage with universities and research organisations, it is encouraging that informal engagement may be sufficient to encourage innovation in some sectors. However, Koch and Strotmann (2008) only considered the knowledge intensive business services sector – services such as management consultancy, software and accountancy – and this equivalence between formal and informal access appears not to hold for manufacturing, where the optimal result requires both mechanisms (Grimpe & Hussinger, 2013).

Recent years have seen a push for increasing public engagement with research. The European Commission's *Horizon 2020 European Union Framework Program for Research and Innovation* includes public engagement as a requirement for responsible research and innovation, with the primary benefits of public engagement being[30]

- The development of a scientifically literate society that is able to actively participate in democratic processes relating to science and technology (for example ethics and evaluation);
- The inclusion of different perspectives and increased creativity in both the design of research activities and interpretation of results; and
- The fostering of research and innovation which is more relevant and addresses challenges considered important by broader society.

The UK Science and Technology Facilities Council encourages holders of its research grants to spend up to 1% of the grant funds on engagement or 'public understanding' work with the proviso that these funds should be found from project savings[31]. While the Council does offer grants for specific engagement projects and allows for funds to be aggregated, this approach does appear to send a mixed message.

To be done well, public engagement requires a combination of committed resources, enthusiastic researchers and supportive management. Involvement in public engagement will often compete with other priorities that are far more influential in terms of rewards for individual careers and departmental budgets:

> *"... at most institutions, although education and outreach activities are seen as important, they are usually not rewarded, nor are they given much weight in tenure and promotion decisions. Thus, education and outreach often become activities that are seen as 'something you do on your own time.'"* (McCann, Cramer & Taylor, 2015).

Funding grants are available to support engagement activities, both from government, philanthropy and learned societies. But this funding is usually

[30] http://ec.europa.eu/programmes/horizon2020/en/h2020-section/public-engagement-responsible-research-and-innovation; accessed 19th April 2016

[31] http://www.stfc.ac.uk/funding/public-engagement-funding/; accessed 19th April 2016

directed towards discrete programs and is not necessarily integrated with ongoing research activities. The UK Science and Technology Facilities Council request above does help researchers to begin seeing engagement as an integral part of their research program. Similarly, the Wellcome Trust allows researchers to include a *Dedicated Provision for Public Engagement* in requests for research grant funding[32]. These types of initiatives will help to shift public engagement from being an add-in extra that you do in your own time to an integral part of the research process.

Public engagement can occur at any time in the research continuum, from involvement in formulating the research question, collecting and analysing data ('citizen science'), to targeted dissemination and public lectures. Impacts arising from these engagements will be notoriously difficult to identify and track, as they are likely to be based in the notions of a well-informed citizenry and providing inspiration. The reach of public engagement activities is relatively easy to determine through audience and similar counts. These activities vary greatly in relation to the depth of the engagement and the link between an engagement activity and any outcomes can play out over a very long period of time with myriad contributing factors. There is a tendency to consider engagement as impact, but public engagement metrics are a measure of activity and a proxy indicator of potential for impact. Engagement activities are a method by which impact can be achieved – they are not impact in itself.

[32] http://www.wellcome.ac.uk/Funding/Public-engagement/Engagement-with-your-research/Funding-within-research-grants/index.htm; accessed 1st April 2016

# Chapter 8: Correlations & Causalities - Looking for Reasons

*"This focus on attribution is the hallmark of impact evaluations. Correspondingly, the central challenge in carrying out effective impact evaluations is to identify the causal relationship between the project, program, or policy and the outcomes of interest"*

– Gertler, Martinez, Premand, Rawlings & Versmeech, Impact Evaluation in Practice, 2011

Assessing impact requires that a direct link must be made between the research work and the observed effect. But as any experienced researcher knows, causality can be a very difficult thing to prove. Correlation between any two components of a complex process is much easier to find, but as is well known, correlation is not causality and correlations can be meaningless or even misleading.

As we enter the age of big data, identifying correlations is becoming ever easier. Advances in computing power, data capture and analytics is allowing previously unseen patterns and presumed relationships to be discovered. Cowls and Schroeder (2015) suggest that for business purposes (for example, predicting purchasing behaviour) correlation may be sufficient but it is not enough for the meaningful advancement of knowledge. Looking for patterns in the data can identify relationships that warrant further investigation, but it cannot be used to definitively attribute causation. In the words of An (2010),

> *"Although correlative patterns may provide the foundational basis of causal hypothesis development, the scientific method mandates an additional step: experimental evaluation of causality."*

Writing about biomedical research, An (2010) suggests we now have a bottleneck, where the identification of correlations fast outstrips our ability to test in a given time frame the many complex, multi-causality relationships that may be underpinning the correlation. This presents challenges for policy makers. If we are attempting to assess impact, then correlation is of little interest to us, apart from ensuring that we do not mistake correlation for causality.

For some aspects of impact, in particular cases, it can be relatively easy to trace some causality: if research results in a new product which then sells millions of units, the presence of a causal relationship is obvious. But if research is used to inform a component of a suite of policy and regulatory changes, it becomes far harder to determine what contribution, if any, the work has had to any resulting behavioural changes. Even with our sales example, there will be other activities such as marketing, which have contributed to the ultimate size of the impact, but it will be relatively easy to demonstrate the necessity of the research: without it there would have been no product to take to market.

The evidence needed before accepting causality can vary according to the context in which it is required. In scientific terms, the association must be statistically significant and ideally should be demonstrated by the use of randomised controlled experiments. For legal purposes, causation may be proved *on the balance of probabilities.* In this situation, it is enough for the causation to be more likely to be true than not (Mengersen, Moynihan & Tweedie, 2007). Between these two extremes lies the concept of *practical causality* where Bayesian analysis can be used to estimate the probability that a relationship is causal (Gastwirth, 2013).

Obviously the use of random trials or major statistical analyses to definitively prove the causal relationship between a piece of research and an impact is impractical, adding greatly to the time and resources required to undertake assessments, or in many cases, impossible. In the absence of randomised controls and rigorous statistical analysis some researchers may be reluctant to describe their work has having a causal relationship with an observed impact, effectively disadvantaging them when being assessed.

Maybe the strength of the causal link is not very important when attempting to assess research impact. Rather, what counts is simply the presence of a link. Or should researchers expect that those assessing them adhere to the same standards of causal proof that they apply to their work? In which case, should that link be externally validated, independently of the research whose work is being assessed? Again, this is likely to require time and resources that may be far better spent supporting actual research.

It is human nature to infer causation from patterns and associations that are presented to us. These inferred causations tend to support our intuitive notions and preconceived ideas (Bleske-Rechek, Morrison & Heidtke, 2015). If we accept the notion that end-users are often better placed to assess impact than research peers then we must also accept that our assessors will include people who may not be as familiar with the distinctions between correlation and causation.

## 8.1: Playing Numerical Games

When choosing metrics or indicators for use in impact assessment, or indeed any assessment, it is important to keep in mind that some metrics can be relatively easy to manipulate in order to meet perceived targets. These are generally metrics which are initiated by the organisation being assessed, and do not rely on independent external validation before becoming countable. Innovation metrics relating to patenting are a pertinent example of the ability of individuals and organisations to 'game' the system when there is funding at stake.

As has been previously discussed, patenting data is often used as a measure of innovation activity. Patenting is a long and expensive process, and while eventual granting of a patent is an independent verification of the novelty of an idea, it makes no claims as to the commercial viability of the idea. Many organisations report on numbers of patent applications submitted each year and then track their progress through the system. For example, in its 2012-13 Annual Report Australia's Commonwealth Scientific and Industrial Research

Organisation (CSIRO) reported the number of current Patent Cooperation Treaty (PCT) applications and the number of granted patents held, along with data relating to inventions trademarks, registered designs and plant breeders rights (CSIRO, 2013). The resources required to support patenting activity can disadvantage smaller organisations compared to their better-resourced peers. Commercialisation staff can always find some new inventions to disclose in order to meet their quarterly key performance indicators (KPIs).

Indicators and metrics for use therefore must be chosen carefully. They must be robust, and not easily manipulated. The sources from which the data is obtained must be of high quality and timely. If indicators are constructed from aggregated data the method of construction must be transparent. Gingras (2014) suggests, at a minimum, for an indicator to be valid requires three essential criteria to be fulfilled:

1. Adequacy of the indicator for the object it measures – does it faithfully correspond to the concept being examined?

2. Sensitivity to the "intrinsic inertia" of the object being measured – does it change in ways that are consistent with the ways in which the concept itself changes?

3. Homogeneity of the dimensions of the indicator - does the indicator combine different types of data?

Gingras (2014) is particularly critical of composite indicators such as the *Shanghai University Ranking* and the *h*-index due to the inability to clearly identify what is driving changes and thus they do not assist policy makers and managers in decision making. In examining a number of indicators, including some used for university rankings, Paruolo, Saisana and Saltelli (2012) conclude that while indicator developers will often explicitly present the weighting methods and rationales, the implications of them tend not to be well understood, or even assessed. They note composite indicators are often composed by using linear aggregation and severe errors can occur when the weight of the variable deviates substantially from its relative strength when determining what order the item being evaluated should be ranked (Paruolo et al, 2012). Piro and Sivertsen (2016) suggest for particular university rankings, differences in the number of research staff may be a key driver behind a university's final position and year to year changes may be the result of relatively rare exceptional events. While there is much merit in these arguments the reality is these types of composite indicators have become well-established and it will take considerable education to ensure their responsible use.

Utilising a suite of indicators rather than attempting to construct a single one is still a difficult task. In looking at fourteen commonly used research indicators used in UK universities, Tee (2016) suggests while all had some relevance, none had particular merit as a single good indicator. Many of them are used in the determination of university rankings, yet they tend to be focused on the sciences and may be biased in favour of a small number of disciplines (Tee, 2016).

The key to choosing indicators or metrics for use in assessment is dependent on what you are trying to achieve from the assessment – why is it being undertaken? The most common reasons given for research impact assessments are really variations on the idea of ensuring the public gets value for money from investment in research. This is generally done via determining the value of past research and then using this information to inform strategies for the future direction of funding, in the (possibly mistaken) belief that past performance indicates future performance.

Impact assessment is based on past performance and as such, funding decisions should not be totally reliant on this assessment, particularly if the assessment is based on metrics and indicators. The Council of Canadian Academies Expert Panel on Science Performance and Research Funding (2012) found that

> *"Mapping research funding allocation directly to quantitative indicators is far too simplistic, and is not a realistic strategy….In most respects, neither the existing body of evidence nor the experience of international funding processes justifies a simplistic funding allocation based solely on*

*quantitative indicators. … the Panel found no evidence that there is a single correct funding response to any assessment results".* (Council of Canadian Academies, 2012).

It may be, that when it comes to the impact of research outside the academic sphere, numerical indicators do not add sufficient value to the decision making process. Yet, they will always be appealing as a numerical ranking gives the appearance of subjectivity having been removed from decision making, when the reality is that the choice and weighting (if used) of individual numerical indicators is subjective in itself.

## 8.2: Tracing Lineage

*"… If I have seen a little further it is by standing on the shoulders of giants".*

– Isaac Newton, Letter to Robert Hooke, 1676

Isaac Newton's correspondence to Robert Hooke is commonly interpreted as Newton acknowledging that intellectual breakthroughs do not happen in isolation, but, rather, science advances by continually building on the work of those who have gone before. Further refinement of Newton's statement suggests it is not necessarily all those who have gone before, but those of high standing and quality. This is in contrast to the situation suggested by Ortega y Gasset that high quality research requires a critical mass of lower quality research to support it (Bormann, de Moya Agnegón & Leydesdorff, 2010). Bormann et al (2010) uses citation analysis to conclude the validity of the Ortega Hypothesis, as it is known, is questionable. They also looked at Turner and Chubin's Ecclesiastes Hypothesis, the notion that an evolutionary model of science results in advances due to chance or luck, and found citation analysis does not support this idea either. Bormann et al (2010) conclude high quality research (as a proxy for impact) predominantly builds on other high quality research and thus one way of maximising the impact of funding schemes is to focus on funding only those already proven to be excellent researchers.

Regardless of the status or quality of those giants who have gone before, they exist. As time passes, their contributions can become part of the inherent background knowledge for their field, no longer receiving specific citation credit. This situation is sometimes referred to as 'obliteration by incorporation' (McCain, 2014), and can be defined as

> *"…the obliteration of ideas, methods, or findings by their incorporation in currently accepted knowledge."* (Merton, 1988).

Developers of new techniques and research equipment may be remembered by name (for example, Ouchterlony Double Immunodiffusion), which is referenced in the experimental method, but not in the official citations of a publication. Theories, principles and methodologies may also travel through time with a name attached (for example, Bayesian analysis). Where concepts remain attached to their instigators name in this way they will be cited implicitly and full text searching will capture their influence when not cited explicitly. But where the name and concept have parted company there is less chance of recognition.

A listing of the most-cited papers recorded in Thompson Reuters' *Web of Science* produced for the journal Nature found that very few of the most widely recognised breakthroughs are among the most highly cited papers (Van Noorden, Maher & Nuzzo, 2014). While based on a single dataset, the analysis suggests the most cited papers are generally those which present experimental methods or tools that have gone on to become essential for researchers working in the field (Van Noorden et al, 2014).

Macdonald (2015), when discussing peer review, bluntly states

> *"…peer review masks the reality that papers stating the blindingly obvious and the universally applicable are the most readily cited. Unless top journals publish such papers, they soon cease to be such papers."*

Marx (2011) suggests citation counts of those papers considered to be seminal in their fields will underestimate their influence as the work quickly becomes integrated into textbooks and teaching, becoming part of the common canon of its community of users. Similarly, Van Noorden et al (2014) postulate one reason why breakthrough discoveries may not be cited as often as expected is because their importance results in rapid incorporation into textbooks and the general body of knowledge so that it is considered familiar enough not to require explicit citation. *Reference Publication Year Spectroscopy* (RPYS), a quantitative method for assisting in tracing the origins of a research field has been posited as a way to help identify these vital papers (Marx, Bornmann, Barth & Lleydesdorff, 2014).

Review papers provide valuable overviews of the development of, current state of and contributors to their topic. As such, they provide a convenient means of summarising much of the background relating to a specific piece of research work. However, by citing a review paper, researchers may be mistakenly attributing an idea to the person who first introduced it to them (the review writer) rather than the originator of the idea. The editors of Nature Chemical Biology (2010) caution against overuse of review article citations on the basis that the connectedness of research as demonstrated by the scientific literature may become obscured or biased. Their suggestion is while it is appropriate for review articles to be cited, most citations should be of the original work, especially when referring to concepts or results (Nature Chemical Biology, 2010). However, Lachance, Poirier and Larivière (2014) found no evidence that being cited in a review paper leads to a decrease in citations of the original paper, and this would accord with the way many researchers use review papers as a means of identifying important papers for closer study.

Citation allows us to track the influence of a published piece of research within the scientific literature over a period of time. It provides a family tree of publications which have led to the end result, along with the names of the giants. But just as our own family trees can have unexplained gaps, incorrect names, second marriages, interlopers and family secrets, so too can the publication tree be inaccurate and incomplete on occasions.

When it comes to assessment, most of those being assessed will be more concerned with not receiving proper credit than with receiving that which is undue. Analysis of implicit citations, acknowledgement practices and research networks may help to identify some of those whose contribution has not been formally acknowledged by citation. Again, just like our own family trees, the further back in time we travel the more difficult it becomes to accurately identify predecessors. Yet these are the true foundations on which the work stands. An item of research which is being assessed for impact may not have any traditional scientific literature attached to it. But surely the forbears of this work have just as much right to recognition as those whose descendants appear in the best journals.

## 8.3: Data Collection and Impact Assessments – Avoiding a Growth Industry

Research impact assessments rely in the first instance on identifying a piece of research work and then tracking the outputs of that work through outcomes and eventually impacts.

Outputs are generally well captured. Publications and patents are recorded in centralised external data repositories. Funding bodies often require reporting on publications and patents arising from a particular grant. To date, systematic attempts to collect outcomes and impacts have been far rarer. There are a number of projects around the world attempting to address this, often by focusing on the development of taxonomies and systems: Star Metrics[33] in the US, MICE[34] in the UK, Lattes in Brazil[35], Researchfish[36] in the UK (see Penfield et al, 2014, for an overview).

Studies by the US Federal Demonstration Partnership have found that faculty members spend more than 40% of their Federally-funded research time on

[33] https://www.starmetrics.nih.gov/ accessed 20th December 2014
[34] https://kclpure.kcl.ac.uk/portal/en/projects/measuring-impact-under-cerif-mice(4878db72-4479-4f29-b355-fae331c2669d).html accessed 20th December 2014
[35] http://lattes.cnpq.br/ accessed 20th December 2014
[36] http://www.researchfish.com/ accessed 20th December 2014

associated administrative tasks rather than actively doing research (Schneider, Ness, Rockwell, Shaver & Brutkiewicz, 2014; Decker, Wimsatt, Trice & Konstan, 2007). If this holds for similar groups around the world then it becomes apparent that minimising the burden associated with tracking and assessing impact is a key requirement of any impact assessment exercise.

Any research assessment exercise must be cost effective, both for those who require the assessment and those who bear the burden of collecting evidence for assessment. Not all assessments are worth undertaking, with costs that far outweigh the value of the program being assessed. Large, periodical assessments may be worth the investment, if they will inform policy for many years to come. The US Department of Defence *Project Hindsight* assessment took around six years to complete and involved more than 200 people in the mid-1960s, but continued to guide planning and decision making for defence research and development for nearly forty years (National Research Council, 2012).

In a practical sense, the most effective ways to minimise the burden of assessment for participating researchers are through the reuse of data already being collected, and via automated data mining and collection. This then imposes limits on the ability to provide context and explore some of the more nuanced aspects of impact. The ease of data availability may inadvertently result in certain types of impact being viewed more favourably, or as a preferred impact. In accordance with Gingras' (2014) requirements for validity of indicators, any data sources which are utilised in this way must be robust, reliable, transparent and timely. Metric and indicator values themselves must be placed in context. Sales of 100,000 units may not sound very impressive, until you also add that the potential global market is estimated to be 500,000 units and each unit sells for $3.5 million.

Context and nuance are generally provided by case study or narrative approaches to data collection. These narratives can be supported by evidence such as metric and indicator data or stakeholder and end-user testimony. Less amenable to automation, narrative approaches tend to be more time consuming, both for the preparers and the assessors. Penfield et al (2014) note narratives are written with a particular audience and perspective in mind. The reality is that what gets included and emphasised in a prepared case study will be influenced by why the assessment exercise is being performed and what is ultimately at stake. These different perspectives can present difficulties to critical assessment and limit re-use. Most researchers will have had extensive experience in having to present the same basic information about the work in myriad ways to satisfy various reporting requirements.

Of particular concern regarding reliance on narrative studies is the potential for better-resourced research organisations to be unfairly advantaged. The introduction of new assessment and new funding models tends to be followed by new consulting and professional services to help organisations maximise their returns. Influential writing skills and resources to track and collate evidence will likely contribute to more favourable impact assessments. In the United Kingdom, new university positions have been created and companies are now offering contract services for creating impact case studies (Penfield et al, 2014). In reference to the UK Research Excellence Framework (REF) the Department for Business Innovation and Skills noted

> *"We must also address the 'industries' that some institutions create around the REF and the people who promote and encourage these behaviours. There are cases of universities running multiple 'mock REFs', bringing in external consultants and taking academics away from teaching and research. These activities appear to be a significant driver of the cost estimates cited above. These behaviours will be difficult to shift, but it will be important to consider the levers and incentives within the design of the REF and to guard wherever possible against unintended consequences."* (Department for Business, Innovation & Skills, 2015a).

It would seem that in terms of creating a new impact assessment industry, we are already well on the way.

# Chapter 9: The Place for Peer Assessment

*"Why do we put up with it? Do we like to be criticized? No, no scientist enjoys it. Every scientist feels a proprietary affection for his or her ideas and findings. Even so, you don't reply to critics, Wait a minute; this is a really good idea; I'm very fond of it; it's done you no harm; please leave it alone. Instead, the hard but just rule is that if the ideas don't work, you must throw them away."*

— Carl Sagan, The Demon-Haunted World: Science as a Candle in the Dark, 1995

The peer review process as practiced today to administer the dissemination of scientific knowledge is generally recognised as having its origins in the mid 1700s. Based on practices utilised by the Royal Society and the Royal Society of Edinburgh, items submitted for publication were reviewed by a group of Society members with relevant expertise who then made recommendations to the editor (Spier, 2002; Lee, Sugimoto, Zhang & Cronin, 2013). Despite this long history, peer review for journal publication really only became widespread in the second half of the twentieth century (Macdonald, 2015). Peer review is considered necessary to maintain the integrity of the scientific record due to its contribution to the community's self-correcting mechanisms

## 9:1: Pitfalls

In recent years, concerns have been raised about the integrity of the peer review process, particularly in relation to academic publishing: charges of bias; undisclosed conflicts of interest; inability to detect fraud and misconduct; stifling of ideas outside the orthodox; and high costs (both in time and money), have all been levelled at peer review (Benos et al, 2007; Lee, Sugimoto, Zhang & Cronin, 2013; Jubb, 2016). Misconduct by authors appears to be more common in the higher ranking journals, reflecting the growing pressure to publish in top journals (Fang, Steen & Casadevall, 2012). The rise in open access journals has been accompanied by a rise in 'predatory' publishing activities where peer review may be negligible (Bartholomew, 2014; Bohannon, 2013; Bowman, 2014) further diminishing trust. Worryingly, Bohannon's (2013) testing of publication acceptance processes found that journals from established academic publishers such as Elsevier, Sage and Walters Kluwer accepted papers which should not have passed peer review. In the same test, open access journal PLoS ONE evidenced the most rigorous review process prior to rejecting the paper, demonstrating that the problem is not with open access *per se*, but rather with unscrupulous practices, inadequate processes and sloppy review (Bohannon, 2013).

It has been suggested there has been a shift in the reason for publishing from the public good of disseminating knowledge to the private good of promotion and reputation enhancement (Macdonald, 2015). The rise of 'publish or perish' along with other changes in the academic environment led Macdonald (2015) to question if peer review is transforming into an estimation of the likelihood of a paper to be cited rather than the soundness of the work. In Macdonald's (2015) view, in our current environment, achieving favourable peer review, whether demonstrated through publication in high impact journals, success in grant funding or climbing university rankings, is now a core part of the business strategy for many universities. This loss of confidence in the publication peer review process is also affecting peer assessment.

Peer assessment of research can be found at all stages of the public funding cycle. Many programs rely on research practitioners recommending proposals for funding. The criteria used to select proposals will vary according to the specific aims of the project. Research track record, innovation, feasibility of approach to be used, national benefit, capacity building, support from the administering institution, industry co-investment and collaboration are all utilized in various Australian funding schemes (Australian Research Council, 2013a, 2013b, 2014). Vieira and Gomes (2016) report that composite bibliometric indicators can provide a reasonable prediction as to which funding applications will be ranked highly by peer review. As the funding program examined by Vieira and Gomes (2016) weighted the *curriculum vitae* of applicants as contributing 60% to the assessment and the bibliometric indicators were compiled from the publications listed on the same *curriculum vitae* used by the reviewers, it would be a major concern if there was not a strong correlation.

Yet for all the effort that goes in to the peer review of funding applications, it may be that it does not necessarily result in significant improvements in the quality of research being undertaken, at least as understood by the academy itself. In 2007, Demicheli and Di Pietrantonj's Cochrane Review found there had been no studies on how peer review of grant applications might affect the quality of the resulting research. Since then, a review of 1,500 US research grants awarded under the R01 program found there was no appreciable difference between the number of publications, nor resulting citations, arising from projects ranked as high or low priorities for funding (Danthi, Wu, Shi & Lauer, 2014). This is despite potential for impact being included as a major criterion for consideration. Analysis of a larger set of R01 grants awarded between 1980 and 2008 (130,000 grants) did find higher citation numbers, higher publication numbers and higher patenting levels are associated with applications receiving higher peer review scores (Li & Agha, 2015). From this, Li and Agha (2015) conclude that peer review does add value in the assessment of applications, but there is further work to be undertaken, especially if considering the costs involved and desired outcomes. Analysis of 2,063 American Institute of Biological Sciences (AIBS) assessed grants shows a moderate correlation (Gallo, Carpenter, Irwin, McPartland, Travis, Reynders, Thompson & Glisson, 2014). In noting that their finding contradicts that of Danthi et al (2014), Gallo et al (2014) suggest the use of standing review panels by the National Institutes of Health compared to ad-hoc panels convened for AIBS applications may contribute to this difference.

It would seem the effectiveness of peer review is not clear-cut. The CEO of Australia's National Health & Medical Research Council (NHMRC), Warwick Anderson, acknowledges that peer review, especially when determining grant funding, can never be a precise instrument; that it will always require human judgement and cannot be reduced to a single number (Anderson, 2015). Previously, former editor of the British Medical Journal, Richard Smith, concluded that, similar to Winston Churchill's declaration regarding democracy,

> "*… peer review is a flawed process, full of easily identified defects with little evidence that it works. Nevertheless, it is likely to remain central to science and journals because there is no obvious alternative, …*" (Smith, 2006).

Despite the flaws of peer review, alternative methods of allocating funding such as lottery or decision making by a single authority are unlikely to be accepted by researchers. Nor would they necessarily engender public trust in the research funding process.

When undertaken on large scales, peer review is an expensive process. It is a process where many of the costs are indirect or borne by parties other than those requiring the review. Questions are being asked as to whether the costs involved are worth the effort, for both *a priori* and *a posteriori* assessments.

Peer review in the research community rarely involves reviewers being reimbursed for the time they spend assessing grant applications or submitted manuscripts. It is considered to be part of their obligations as members of the research community. The cost of reviewers time is therefore borne by their employing institutions, or more likely the reviewers themselves as much of this work is undertaken outside of normal working hours.

Gordon and Poulin (2009a) suggest the cost of preparing and then peer reviewing National Science and Engineering Research Council of Canada Science grants was greater than the cost of giving each eligible researcher a grant of the same amount as the average awarded grant. This provoked lively correspondence as to the validity of the findings (Roorda, 2009; Gordon & Poulin, 2009b), but there is no doubt the costs associated with preparing applications can be considerable: Kulage, Schnall, Hickey, Travers, Zezulinski, Torres, Burgess and Larson (2015) found each National Institutes of Health R01 grant funded for a US Nursing school represented an investment of between USD$72,000 and $270,000. Herbert, Barnett, Clarke and Graves (2013) report

Australian researchers spent an estimated 550 working years on the preparation of proposals for the 2012 NHMRC Project Grant round, at a national cost of $66 million. This calculation was based largely on time spent as identified by lead researchers after the fact and may represent an under-representation once work undertaken by graduate students and administrative staff is included. On to this must then be added the cost of undertaking assessment of the application, along with the personal costs related to the stress and pressure associated with the grant writing season (Herbert, Coveney, Clark, Graves & Barnett, 2014). From this exercise, the NHMRC distributed at total of $458 million in grant funding, at an average of $626,000 per grant with a success rate of 20.5 % (NHMRC, 2013). Given that more than 50% of applications were considered to be worthy of funding, yet did not receive any due to unavailability (NHMRC, 2013), the national cost of undertaking the round represents funding for at least an additional 100 research projects. If, as discussed earlier, higher rankings by peer reviewers do not necessarily correlate with increased impact then there may be a case for the use of base grants supplemented by competitive funding.

At the other end of the assessment cycle, doubts are being raised as to whether national assessment exercises based on expensive peer review provide any increased benefit compared to bibliometric and scientometric data analyses. The 2001 – 2003 Italian university rankings were determined by peer review at an estimated cost of €10 – 11 million, yet, for the hard sciences at least, the same results could have been found using inexpensively accessed scientometric data (Abramo, Cicero & D'Angelo, 2013). The conclusion that peer review and bibliometric outcomes were similar has been criticised by Baccini and De Nicolao (2016) on the grounds that there were flaws in the statistical methods applied in the assessment agency's original report. It may be the case that the suitability of metrics for peer review depends largely on the metrics being used and criteria examined under peer review. In 2006, van Raan reported correlations between peer-review and some citation-based indicators could also be dependent on the size of the group being evaluated.

The UK's 2014 Research Excellence Framework (REF) assessment is estimated to have cost £246 million, with around £55 million of that being the cost to universities of preparing submissions (Farla & Simmonds, 2015). The government appears to be considering an increased use of metrics in the REF as a means to address the bureaucratic and financial burdens associated with the exercise (Department for Business Innovation & Skills, 2015a). Wooding, Van Leeuwen, Parks, Kapur and Grant (2015) found that while changes in the quality of research between 2008 and 2014 as assessed via the peer review process was matched by an increase in publication quality as assessed by bibliometric measures, the relationship is not linear nor straight forward. They conclude that while bibliometrics are only one measure of scientific quality and cannot replace peer review, when there is a significant difference between the results of peer assessment and bibliometric analysis, this suggests there needs to be further investigation undertaken (Wooding et al, 2015).

The Higher Education Funding Council for England (HEFCE) found

> *"… individual metrics give significantly different outcomes from the REF peer review process, showing that metrics cannot provide a like-for-like replacement for REF peer review. "* (HEFCE, 2015a)

This is in contrast to Butler and McAllister's (2009) earlier finding that citation rates, particularly for journal articles, was a good indicator of eventual departmental scores for Political Science in the 2001 quality assessment exercise. Given what we know about the differences in publication and citation practices across disciplines this difference in conclusion should not be surprising. Indeed, Butler and McAllister (2011) themselves subsequently showed this did not hold true for Chemistry, where external income was the most important indicator, followed by citations. The Council further reports correlation of metrics with REF score is significantly affected by the year of publication for research outputs and suggests there may be particular issues when assessing early career and women researchers (HEFCE, 2015a). Therefore, it recommends metrics alone cannot be used to assess quality as defined under the current REF, nor is it feasible to use quantitative indicators for assessment of research impact (Wilsdon et al, 2015). As an interesting side note, Butler and McAllister (2009) found that after journal article citation, the second strongest indicator of the assessment exercise outcome for political science was if there was a member of the department serving on the assessment panel. Butler and McAllister (2009) suggest this may be due to the increased knowledge about the process this person brings back to their department, implying a causal relationship. However, it is possible the causal relationship flows the other way: higher performing researchers are often found in higher performing departments and may be more likely to be asked to join the panels.

Given that, as discussed earlier, world-class research is that recognised as such by peers, it is hard to see peer review disappearing totally from institutional assessment exercises, regardless of the pressures to minimise cost and effort burdens. It is equally clear that while the intelligent use of appropriate indicators within the right context can help to lessen the burden for some disciplines, metrics should not be used as a replacement for contextual review.

## 9.2: Choosing Your Peers in the New ICT Environment

Peer assessment, whether used in allocating research funding or assessing outcomes, is, by definition, undertaken by those who also possess expertise within the discipline area in which you are operating. For those working in multi- and trans-disciplinary areas determining exactly who are your peers, or more importantly, who is best placed to assess your impact, can be particularly difficult.

The medical research community has often led the way in developing frameworks and indicators for research impacts (for example, UK Evaluation Forum, 2006; Canadian Academy of Health Sciences, 2009; *Becker Medical Library Model for Assessment of Research Impact*[37]), yet there would still appear to be concerns regarding who should be carrying out the assessment of impact. In their analysis of 32 health research impact studies Milat, Bauman & Redman

[37] https://becker.wustl.edu/impact-assessment/model

(2015) found end users were rarely involved in the assessment process whereby

> *"... only four interviewed non-academic end-users of research in impact assessment processes, with the vast majority of studies relying on principal investigator interviews and/or peer review processes to assess impacts."*

In finding that almost 40% of Australian health intervention research had impacted on either policy or practice, Cohen et al (2015) relied on an expert panel of intervention researchers, of whom one third had experience in government policy setting. This reliance on researchers to undertake assessment is likely to result in assessments which are heavily influenced by traditional academic assessment values, even if subconsciously. Of more concern is that those with vested interests may be presenting cases without independent verification being available. Similar to Bozeman and Boardman's (2009) contention that scientists are not necessarily any more qualified to decide what is good for society than any other citizen, it does raise the question of whether researchers are the best people to assess the impact of their research.

This leads us to the conclusion that impact assessment should be undertaken by those with detailed knowledge of the end-user community and experience. This issue was addressed by the 2012 *Excellence in Innovation for Australia (EIA) Impact Assessment Trial*, administered by the Australian Technology Network of Universities with 70% of review panel members recruited from outside the higher education sector (Morgan Jones, Castle-Clarke, Manville, Gunashekar & Grant, 2013). The 2014 UK Research Excellence Framework assessment panels included fifteen research users drawn from cultural institutions, finance institutions, industry and philanthropic institutions (Manville, Guthrie, Henham, Garrod, Sousa, Kirtley, Castle-Clarke & Ling, 2015). It should be kept in mind there must be consistency between the type of impact being assessed and the expertise, values and priorities of those undertaking the assessment. This is particularly so when there is potential for conflict between impact areas. It is reasonable to expect that research identifying the sensitivity of endangered species to environmental disruptions resulting from mining activity will be assessed very differently by someone from an environmental non-profit compared to an economist specialising in the resources sector.

Inter- and trans-disciplinary research by definition crosses disciplinary boundaries. A high impact issue may require a relatively simple engineering solution combined with a difficult medical solution. Engineering peers may view this as not worthy of funding from their perspective, while medical peers may consider it crucial. For those undertaking research under the new ICT paradigm, who are your peers? The answer to this question can determine if you receive funding, if your potential for impact is recognised and how actual impact is valued. In most countries, researchers allocate their funding requests and reporting to discipline groups by the use of codes such as the ANZSRC. Researchers have always been aware of the need to select these codes with care to ensure the most appropriate review panel is used. To this we can now add a requirement to be strategic about the way these codes are used to ensure work is examined by the panel which will be able to best recognise the potential for impact rather than just the merit of the research question.

# Chapter 10: Where to From Here?

Many developed nations are now moving towards public research funding systems that include impact assessment in the mix of considerations for awarding funding. This can be at both the level of funding for individual projects and for institutions. In the United Kingdom, £1,573.3M was expected to be distributed as part of the Research Quality pool in 2015/16, based on the outcomes of the Research Excellence Framework 2014 (REF 2014) assessment exercise covering 52,000 researchers (Department for Business, Innovation and Skills, 2014a). The Department of Business, Innovation and Skills (BIS) also funds the Research Councils, the Academies and other science and research initiatives in the UK and expenditure relating to REF 2014 represents approximately one third of their expenditure on science and research. As an aside, the fact that the source of most of the UK university sector's research funding is one which describes itself as '*the department for economic growth*' (Department of Business, Innovation and Skills, 2014b) is revealing in itself of a paradigm shift towards science and research being supported by governments to serve the interests of the economy rather than of society more broadly. De Freitas, Mayer, Arnab and Marshall (2014) describe this as

> *"… a trend of how universities, once seen as an engine of the economy, are now being regarded as a service, as part of the wider socio-economic trend towards greater service-orientated provision where universities provide a service to industry, not just in terms of employment but also for adding valuable commercial advantage to the industry."*

In an increasingly competitive environment, the use of impact as a factor in determining who receives funding is laudable. However, there are questions that need to be asked about its validity, especially when it becomes a factor in determining funding awarded to individual researchers for their projects.

In Australia, twice as much research and development work is carried out within the higher education sector than in the government sector, including publicly funded research bodies (OECD 2014). While a significant portion of this research is funded by industry, in common with many OECD countries the majority of publicly funded research in Australia happens within its universities. In 2015, the main public funder of Australian university research, the Australian Research Council, awarded $67.5M for new research grants in the eleven ANZSRC 4-digit fields of research where the majority of ICT research is undertaken[38]. This represents 7% of the research funding grants awarded by the ARC that year.

During the period 2002 to 2014, grant funding to universities to undertake research in these ICT-related areas averaged 8% of ARC grant funding, ranging from a high of 14% in 2003 to a low of 5% in 2011 (Table 20; Table 21). While this is a relatively small investment in such an important area we must keep in mind that there will be some research occurring in other fields of research that will fit our expanded definition of ICT. Also, during almost the same period, the ARC invested more than $300M in the national ICT centre of excellence, NICTA, with this amount matched by the Commonwealth Department of Broadband, Communications and the Digital Economy[39]. NICTA's structure as a university/government joint venture means that a significant portion of this funding supported research undertaken in close partnerships with universities. State governments also contributed funding to support research undertaken by NICTA and the Commonwealth also funded a significant amount of ICT research via the CSIRO.

In 2016, NICTA was incorporated within CSIRO's ICT research division to create Data61, with a commitment of $75M Commonwealth funding[40]. At this point in time it is not clear what effect, if any, this change will have on the ARC's funding of ICT research in universities.

[38] ARC Research Funding Trend Data ; excel format; http://www.arc.gov.au/grants-dataset; accessed 13 November, 2016

[39] http://www.arc.gov.au/fact-sheet-national-ict-australia; accessed 13 November, 2016

[40] http://www.innovation.gov.au/page/data61-australias-digital-and-data-innovation-group; accessed 13 November, 2016

| Main Fields of Research Contributing to ICT | | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|
| 0801 | ARTIFICIAL INTELLIGENCE AND IMAGE PROCESSING | $4,926,683 | $18,110,295 | $6,289,102 | $8,922,830 | $12,816,174 | $7,694,560 | $8,980,298 |
| 0802 | COMPUTATION THEORY AND MATHEMATICS | $1,230,501 | $2,696,307 | $3,923,886 | $2,534,000 | $1,210,886 | $1,057,454 | $1,313,492 |
| 0803 | COMPUTER SOFTWARE | $3,085,923 | $3,248,976 | $2,790,751 | $4,058,280 | $3,738,447 | $3,053,166 | $2,999,192 |
| 0804 | DATA FORMAT | $1,339,628 | $2,146,297 | $1,933,736 | $2,324,463 | $2,369,736 | $2,805,694 | $1,735,186 |
| 0805 | DISTRIBUTED COMPUTING | | | | | | | |
| 0806 | INFORMATION SYSTEMS | $4,128,272 | $5,741,183 | $8,476,458 | $5,940,303 | $6,538,161 | $4,510,189 | $6,413,036 |
| 0899 | OTHER INFORMATION AND COMPUTING SCIENCES | | | | | | | |
| 1005 | COMMUNICATIONS TECHNOLOGIES | $7,440,366 | $29,869,346 | $9,368,345 | $9,345,836 | $7,523,289 | $9,528,538 | $8,072,336 |
| 1006 | COMPUTER HARDWARE | | $180,000 | $945,161 | $423,000 | $1,480,110 | $782,000 | |
| 1099 | OTHER TECHNOLOGY | $202,118 | | $336,706 | | | | |
| 0906 | ELECTRICAL AND ELECTRONIC ENGINEERING | $7,599,875 | $25,079,506 | $8,238,101 | $8,174,023 | $6,353,084 | $5,273,105 | $7,873,165 |
| **Total ICT Fields of Research** | | **$29,953,366** | **$87,071,910** | **$42,302,246** | **$41,722,735** | **$42,029,887** | **$34,704,706** | **$37,386,705** |
| **Total ARC Funding Awarded - All FoRs** | | **$331,040,775** | **$612,694,052** | **$467,868,147** | **$676,777,527** | **$475,595,065** | **$462,854,394** | **$490,580,740** |
| ICT FoRs as Percentage of Total Awarded | | 9% | 14% | 9% | 6% | 9% | 7% | 8% |

**Table 20: ARC Funding of ICT Fields of Research 2002 – 2008 (Data source: ARC Research Funding Trend Data, http://www.arc.gov.au/grants-dataset)**

| Main Fields of Research Contributing to ICT | | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
|---|---|---|---|---|---|---|---|
| 0801 | ARTIFICIAL INTELLIGENCE AND IMAGE PROCESSING | $11,918,030 | $10,429,810 | $12,628,769 | $15,404,553 | $19,505,788 | $34,987,291 |
| 0802 | COMPUTATION THEORY AND MATHEMATICS | $1,450,140 | $4,976,903 | $3,778,416 | $3,102,196 | $1,047,084 | $2,771,492 |
| 0803 | COMPUTER SOFTWARE | $2,444,000 | $2,194,106 | $1,490,300 | $1,220,000 | $2,153,144 | $3,030,591 |
| 0804 | DATA FORMAT | $2,651,270 | $1,441,000 | $1,875,956 | $800,000 | $1,312,036 | $2,811,769 |
| 0805 | DISTRIBUTED COMPUTING | | $686,489 | $1,352,722 | $2,219,024 | $1,276,000 | $616,970 |
| 0806 | INFORMATION SYSTEMS | $5,782,090 | $6,362,416 | $7,368,102 | $6,698,723 | $8,858,451 | $7,840,316 |
| 0899 | OTHER INFORMATION AND COMPUTING SCIENCES | | | $330,000 | $615,000 | $315,000 | |
| 1005 | COMMUNICATIONS TECHNOLOGIES | $14,864,551 | $7,817,136 | $6,716,518 | $5,323,456 | $6,814,000 | $2,249,651 |
| 1006 | COMPUTER HARDWARE | $325,000 | | | $280,000 | $200,000 | $1,000,000 |
| 1099 | OTHER TECHNOLOGY | | $1,014,566 | | $599,966 | | |
| 0906 | ELECTRICAL AND ELECTRONIC ENGINEERING | $6,318,840 | $10,899,015 | $14,161,431 | $10,490,057 | $13,954,218 | $12,203,463 |
| **Total ICT Fields of Research** | | **$45,753,921** | **$45,821,441** | **$49,702,214** | **$46,752,975** | **$55,435,721** | **$67,511,543** |
| **Total ARC Funding Awarded - All FoRs** | | **$656,177,639** | **$685,145,976** | **$954,390,771** | **$735,969,491** | **$705,102,947** | **$1,018,017,312** |
| **ICT FoRs as Percentage of Total Awarded** | | 7% | 7% | 5% | 6% | 8% | 7% |

**Table 21: ARC Funding of ICT Fields of Research 2009 - 2014 (Data source: ARC Research Funding Trend Data, http://www.arc.gov.au/grants-dataset)**

Australia has been grappling with the idea of implementing a research impact assessment exercise for its university sector, and a natural outcome of this is likely to be its use for the allocation of a portion of public research funding, as currently happens in the United Kingdom. While significant changes have just been implemented to simplify the way in which block infrastructure funding is allocated, there is likely to be pressure to incorporate impact results into the allocation process. An alternative is to set aside a portion of the funding to be distributed separately based on impact. Morgan Jones et al (2013) estimate that at a production cost of $5,000 - $10,000 for each Australian impact case study, $100,000 for each case study submitted would need to be available for allocation to make the exercise worthwhile for universities.

Implementing assessment impact as a means to assist in the allocation of research funding is as valid a reason as any other. But it is far more valuable to use impact assessment as a means of determining if your funding program is achieving the goals you have set.

Given the complex nature of the research-innovation ecosystem and the often indirect pathway from research outputs to impacts, mixed method assessment, where a combination of both quantitative and qualitative techniques are used, would appear to be the most appropriate approach to determining impact. Bloch, Sorenson, Graversen, Schneider, Kalpazidou Schmidt, Aagaard and Mejlgaard (2014) point out that

> *"Quantitative approaches are typically linked to positivistic views that social phenomena can be analysed objectively in much the same way as physical phenomena, by making context-free generalizations that can be tested. Qualitative approaches are typically based on an intrepretivistic view that social phenomena must be seen from the point of view of the subject, that behaviour can only be understood in the context of meaning systems employed by a particular group or society."*

with mixed methods attempting to find the middle ground – identifying generalisations within defined contexts.

Mixed methods and qualitative approaches to assessment by necessity utilise expertise to make interpretations and judgements – they cannot be fully automated. As a result, assessment becomes more expensive and time consuming, both for those being assessed and those doing the assessing. Advances in techniques such as data mining and natural language processing have the potential to ease the burden but it is unrealistic to expect they will be able to fully replace human judgement which, while flawed, is far superior when it comes to taking in to account context and ambiguity.

## 10.1: Constructing Your Funding Program

A whole of government approach to research funding necessitates deciding who should be doing the research at more than just the level of grants to individuals and institutions. As we have seen previously, the portion of national research activity being undertaken by industry, universities, government and not for profits varies from country to country. Deciding which sector to direct resources to will depend on political imperatives, the outcomes being sought and myriad cultural factors.

Modelling by Leyden and Link (2014) suggests that in the US at least, government would be better off investing in university research laboratories rather than the government's own laboratories. This is because, within the university, research is undertaken within a broader educational structure and as such is more likely to result in increased human capital and a faster rate of transferring this capital to society. Elnasri and Fox (2014) found in Australia there is

> *"…strong evidence of productivity benefits from public spending on Commonwealth research agencies and higher education. However, the results suggest no evidence of spillover effects on private productivity from public support to the business enterprise sector, multisector or defence R&D"*

Despite suggestions public spending on defence research is particularly poor at creating productivity spillover effects in the wider economy, no one would suggest governments not invest in defence research. Indeed, given that a core rationale for the very existence of the state is the provision of defence, this is a sector where market failure cannot be accepted. In addition, given that much defence research is dual-use, productivity benefits should not be the only measure it is assessed on.

The public support provided by the Australian government to industry examined here was largely in the form of tax credits for spending on research and development. Hence Elnasri and Fox (2014) were comparing indirect support of industry research with direct support of research undertaken by other sectors. One of their concerns is that some items which industry are able to claim as investment in research and development have a tenuous link to what is generally considered to be actual research and development (Elnasri & Fox, 2014). Regardless of how much truth there is in this, it has been noted elsewhere that while industry invests more in R&D in Australia than all other sources combined, this may reflect research activities such as mining exploration which while expensive to undertake are not necessarily labour intensive (Shepherd, 2014), resulting in a dominance of capital investment over job creation. Australian Bureau of Statistics data suggests that in 2013/14 labour costs comprised only 23% of current R&D expenditure in the mining industry, compared to between 45% and 48% in manufacturing, information media and telecommunications and health (ABS, 2015c).

Becker's (2015) review found that recent studies are more likely to show successful stimulation of private R&D using tax credits than earlier studies have. Clearly then, there is a role for this form of research support, but its effectiveness is likely to depend on a number of factors. The answer to these contradictory results may lie in Aghion, David and Foray's (2009) assertion that

> *"The economic payoffs from public programs that aim to promote innovation by supporting private R&D investments are more likely to be disappointing, if indeed the materialize at all, when program design and*

> *implementation decisions fail to take account of the interdependence of the STIG* [science, technology, innovation and growth] *subsystem with the economy as a whole."*

Aghion et al (2009) identify education, competition, macroeconomic levers and labour market regulation as being particularly important policy areas affecting the effectiveness of private R&D support mechanisms.

Elnasri and Fox's (2014) findings do accord with those of Haskel and Wallis (2013), who found a correlation between public support of research via UK Research Council spending and productivity growth, along with a similar lack of spillover arising from spending on defence and government research. An earlier Productivity Commission study also found the correlation between business spending on research and development and productivity growth was not strong in Australia, suggesting that factors such as lag times, other influences and variations between industries may obscure the story (Shanks & Zheng, 2006).

When comparing the effectiveness of tax credits and direct subsidy, Becker (2015) also suggests tax credits are more effective in the short-term, direct subsidies are more effective in the medium to longer-term, and both will be more effective if undertaken in a co-ordinated fashion. This finding regarding short-term and long-term effects at the regional or national level would appear to contradict findings at the company level. Neicu, Teirlinck and Kelchtermans (2016) report the receipt of subsidies tends to be associated with a more strategic use of tax-credits. Clearly there is interplay between the two forms of support and effective policymaking will ensure both are developed as part of a unified approach.

The effectiveness of government support of private R&D is likely to be highly dependent on the stability and maturity of the economy in which it operates. In Colombia it would seem support of private R&D through matching grants and contingent loans (especially through programs which also encourage linkages with universities and government research organisations) leads to improvements in product innovation and total factor productivity at the company level over the mid to long term (Crespi, Garone, Maffioli & Melendez, 2015). Meanwhile, in Argentina, matching grants would seem not to result in any changes in private R&D spending, while fiscal credit mechanisms appear to (Binelli & Maffioli, 2007). In Turkey, both interest free loans and grants have stimulated private spending on R&D, while there appears to be little benefit from tax incentives (Özçelik & Taymaz, 2008).

None of this is to suggest governments should not use policy levers to encourage research and development in the business community. The art is in finding the right types and levels of support. Dai and Cheng (2015) report that in China, there is a minimum level of subsidy required before companies begin to undertake R&D and there is also a level where increasing the level of subsidy does not result in any further increase in company R&D, and may even begin to totally replace the company's own expenditure, a process often referred to as 'crowding out'. Conversely Hong, Hong, Wang, Xu and Zhao's (2015) study of China's high-tech industry found no evidence of crowding out by grants, although they were associated with negative impacts on innovation activity in larger firms. The crowding out phenomenon once subsidies reach a certain level has also been reported in other countries (for example, Gorg & Strobl, 2007), leading Zúñiga-Vicente, Alonso-Borrego, Forcadell and Galán (2014) to postulate that

> *"The effect of public subsidies on private R&D investment might be characterised by an inverted U-shaped curve. Such an effect is positive up to a certain threshold (ie the crowding-in effect would prevail) and negative beyond (with the crowding-out effect dominating)."*

Given Hud and Hussinger's (2015) finding that in 2009 the crowding out effect was also seen in SMEs, it is reasonable to assume that the effect is also highly dependent on financial cycles and credit availability.

In addition to the size of the subsidy, it would also appear the size of the receiving company is also important. Hsu and Hsueh (2009) and Luukkonen (2000) both report that grants and subsidies to SMEs are more impactful than those provided to larger firms. Becker (2015) suggests it would be better government policy to provide smaller levels of support to a greater number of companies, rather than support small numbers of large-scale activities.

Deciding where on the R&D continuum investment should be focused also requires careful consideration. What Szajnfarber and Weigel (2010) describe as

> *"… the need to balance the competing goals of exploration (seeking radical innovation through the pursuit and acquisition of new knowledge) and exploitation (leveraging existing capabilities to enable incremental improvements)…"*

is not only a challenge for individual companies but also for nations as they decide how to support local research and development. March (1991) suggests the first option – exploration – is necessary to ensure a company does not become irrelevant due to changes occurring in either the market or technology, while the second option – exploitation – promotes efficiency, control and certainty.

It has been said of companies that this tension is resolved by a bias towards exploitation given the greater likelihood of short-term success, even though when there is change, companies which do not undertake any exploration are more likely to fail (O'Reilly & Tushman, 2013). The difficulties associated with finding the right balance between exploitation and exploration is complicated by the fact that the structures and characteristics which promote one strategy tend to inhibit the other (O'Reilly & Tushman, 2007). At regional and national levels it is reasonable to expect the same tensions to apply when competing in the global economy.

The value of individual research grants awarded can play a role in achieving some desired impacts. Bloch et al's (2014) Danish study suggests smaller grants can result in significantly higher levels of research publications for every dollar of the grant, suggesting that if your desired impact is an increase in researcher productivity as measured by research output, you are better off giving out large numbers of small grants. (Although Bloch et al (2014) do note publications may be underestimated for larger grants due to likely difficulties in accurately identifying all associated publications). Small grants can kick-start research careers, but larger grants can provide career development support for larger numbers of people (Bloch et al, 2014).

Granting programs are often used to encourage increased collaboration, especially between academia and industry. These can be project based (for example, Australian Research Council *Linkage Projects*) or longer-term consortia-forming (for example, Australia's *Co-operative Research Centres* program). There is no doubt they are successful in increasing interactions as people follow the money, but what is not so clear is how successful they are at initiating new, long-lasting relationships or nudging academic researchers towards more impactful outcomes.

The experience of European Union funded research networks suggests collaborations which are formed specifically to exploit these types of funds do not have any significant effect on researcher productivity (Defazio, Lockett & Wright, 2009). Not all collaborations will survive once the funding ends, as those relationships initiated to exploit the funding opportunity may find there is not enough common ground to develop a longer-term relationship. Meanwhile, a study of the Belgian *Mobilizing Programs* funding program over ten years found that when compared to inter-university networks, the establishment of industry-university networks did not lead universities to undertake more applied or use-inspired basic research (Teirlinck & Spithoven, 2015). In this instance, the program required industry researchers as participants but was not actually successful in its stated aim of attempting to move university research towards more use-inspired and application driven outcomes (and presumably research of higher impact). Teirlinck and Spithoven (2015) suggest an explanation for this may be found in the differing expectations university and industry have in regards to project outcomes (mid-term versus short-term specific solutions) which is compounded by university career structures still being based on scientific outputs.

We have previously encountered this mismatch between reward and recognition systems that individual researchers operate under and the objectives that funders are seeking. De Jong, Smit and van Drooge (2016) frame this as a component of the 'moral hazard' associated with the principal-agent theory of government funding of research. The principal-agent model is based on the idea of resource and information or skill asymmetries between the principal (or purchaser) and the agent (or provider), whereby

> *"Principals seek to manipulate and mold the behaviour of agents so that they will act in a manner consistent with the principals' preferences"* (Waterman & Meier, 1998).

The unequal nature of the amount of information possessed by the participants results in two main difficulties for the participants: moral hazard and adverse selection. The moral hazard exists as the principal never really knows if the agent will put in their best effort while adverse selection is exemplified by the principal not possessing the knowledge to be able to adequately assess which agent is best qualified to undertake the work (Braun & Guston, 2003).

One way of addressing these difficulties is through the use of intermediaries who are considered relatively independent from both the principal and the agent, and are trusted by both sides. For publicly funded research, this role is often fulfilled in regards to adverse selection by quasi-autonomous agencies such as the Australian Research Council, the National Health and Medical Research Council (Australia), the seven UK Research Councils, the US National Institutes of Health and the US National Science Foundation. Research assessment systems (which may be overseen by the same or different agencies) address the moral hazard, while the nature of individual programs can address both adverse selection and moral hazard (de Jong, Smit & van Drooge, 2016).

Like any intervention, there is always the possibility of unintentional consequences, particularly over the long term. Jung and Lee's (2014) study of the commercialisation focused US *National Nanotechnology Initiative* found that contrary to the programs aims, rather than increasing the flow of knowledge from universities to industry, after the program, universities had increased the intake of knowledge from industry. Accompanying this was a narrowing of research scope within the universities and a decrease in successful technology breakthroughs. While positing a number of factors that may have contributed to this finding, Jung and Lee (2014) do conclude that

> *"… the government-initiated emphasis on commercialization and focused research directions may well improve the average economic payoffs by increasing the outcome efficiency in university research. However, these interventions may undermine open paths toward novel technologies and hinder explorations of unknown fields, thereby reducing the chances of achieving breakthrough outcomes from university research. These contrasting outcomes illustrate a potential tradeoff, which is often inherent to many policy programs, between short-term goals and long-term implications."*

Individual researchers must find a way of reconciling the traditional recognition frameworks (scientific excellence) under which most of them operate with the new frameworks (public relevance or impact) that are determining if they receive funding to support their research goals. It has been suggested members of the research community employ a number of strategies to cope with these types of tensions (de Jong, Smit & van Drooge, 2016; Morris & Rip, 2006). Strategies will be highly dependent on the individual and their local environment, but it is worth noting that sometimes just expressing something in a new way can give the impression of compliance, and when requirements conflict with long-held values, human nature will lead many to comply only as much as is minimally required rather than fully. Especially in highly competitive environments, researchers will learn to how to maximise their funding opportunities while continuing to pursue their over-arching research agenda. Evidence is beginning to emerge regarding the ways in which academics approach the requirements of impact statements as part of funding applications and the potential long-term effects on public confidence (Chubb & Watermeyer, 2016).

This suggests that while funding programs can be structured to encourage certain types of behaviour, like many systems, they can be subject to 'gaming', and for long-lasting cultural change should be just one of a suite of activities.

For governments who are trying to use programs as instruments of influence there can be many challenges.

Governments are subject to change, and as such, priorities can change in relatively short time frames. 'Publish or perish' as a cultural ideal has become well entrenched in the research community in response to earlier imperatives around ideas of research productivity. Given that industry-focused research is often not publishable, it will take time for this change in priorities to become settled, by which time government policy may well have shifted again.

As noted above, for researchers, especially those within academia, much of their reward and recognition comes from agencies other than those who are responsible for awarding grant funding. Universities do the hiring and promoting, largely based on publication records, citations, grant success and engagement within the academic profession. Esteem within the field is endowed by peers. This sets up a tension between competing priorities that can lead to sub-optimal results in all areas.

Many areas of research, particularly those in the STEM fields, are highly transportable. The competition for the best researchers is fierce, on an international level. If the majority of funding programs are very narrow in their focus or it just becomes 'too hard' to gain funding, there is a risk that those who are at the top of their field will be tempted by offers from elsewhere.

What does the search for impact mean for those developing funding programs?

Development of impact assessment measures needs to be an integral part of the construction of a funding program. It is not enough for it to be an afterthought. When assessment is not considered as part of the program's development there is a high risk of it becoming disconnected from the goals of the program. It then becomes easier to rely on metrics which are already being gathered. Developing the assessment at this time also allows the wider context, and particularly the decision making context, in which the program is being implemented to inform the match of

> *"… designs and methods to particular program and policy contexts to produce the most useful and actionable evidence."* (Rog, 2012).

The starting point has to be "*what do you want the program to achieve?*" In answering this question, there needs to be a recognition that the more objectives you ask of a program, the less chance there is of meeting any of them. Difficulties also arise if the objective is too broad, outside the parameters of what the program can influence or difficult to evaluate. The program should be part of a suite of activities aimed towards these broader, long-term objectives, but must itself be focused on achievable outcomes within the context the program operates in.

In asking 'what?' one must also be very mindful of the 'how'? What is the pathway by which the different outputs of research contribute to the achievement of your broader goals? This requires a thorough understanding of the local innovation ecosystem and the levers which have most influence on the economy. If a research program is set up with the aim of producing more graduates who go on to create start-ups, it is bound to fail if there is not a clear understanding of the local venture capital environment and its appetite for risk. Having a steady supply of entrepreneurial graduates is going to be of limited benefit if they cannot access necessary capital investment.

When considering how to assess the impact of a research funding program it is necessary to differentiate between the impact of the program itself and the impact of research outcomes arising from the program. Large scale assessment exercises such as the UK REF tend to focus on the impact of research activities with no consideration given to funding sources. As such they do not provide useful information as to the efficacy of funding programs with non-research specific goals, such as increasing university-industry interaction. This suggests that for funding programs which are not targeted towards specific research problems (for example, developing new diagnostics or treatments) research assessment exercises will be of limited value, unless the goal of assessment is increased accountability.

## 10.2: What Impacts Matter? - Prioritising the Indicators

*"An obvious limit on performance measures is that the returns on research are uncertain, long term and circuitous. This makes it difficult to put research into a strict accountability regime. Doing so 'loses sight of the dynamics of science and technology'…"*

- Olsen & Merrill, Measuring the Impacts of Federal Investments in Research, 2011

As the custodians of public monies, governments are charged with the responsibility of spending it wisely. For this reason funding contracts usually include a mix of performance indicators and reporting requirements. Given the uncertain nature of research these indicators will often be around items such as student numbers, additional funds raised, staff numbers, numbers of industry engagements. Other indicators that are commonly used in research for organisational, sectional and individual assessments include proportions of papers in high quality journals and number of patent applications.

The varying nature of performance indicators available is a reflection of what Ewell (2010) describes as

> *"… the conceptual tensions between assessment for accountability and assessment for improvement."*

Ewell (2010) further states that decisions regarding which of these perspectives to adopt will influence what is assessed, how it is assessed and how the results are communicated.

While not always the case, assessment for accountability is more likely to be externally driven while assessment for improvement is often internally driven. It is worth noting that while the 'determining value for money' imperative for assessment can be expressed in ways that suggest a drive for improvement, it is ultimately about accountability – is this the best way to spend money?

In recent years, trust in government and public institutions has declined in many developed economies (Stevenson & Wolfers, 2011; Armingeon & Ceka, 2014; OECD, 2015b). While public trust in science overall remains high, there are issues on which it would seem the public is more ambivalent, especially when these issues are politicised (Resnick, Sawyer & Huddlestone, 2015). High profile misconduct cases such as those involving Japanese stem cell scientist Haruko Obokata (McNeill, 2014), Dutch social psychologist Diederik Stapel (Shea, 2011), South Korean stem cell scientist Hwang Woo Suk (Kakuk, 2009), and US HIV researcher Dong-Pyou Han (Lancet Oncology Editors, 2015) shake public confidence in research and encourage funders to increase accountability measures. Growing reliance on industry funding, with potential real or perceived conflicts of interest, may also lead to scepticism regarding the integrity of research results (Matthews, 2015). Interest groups attempt to discredit study results, individual researchers or the scientific process itself in support of ideologically driven positions in regards to complex, global issues.

Scientific research has often been characterised as self-correcting, with the peer review process and reproducibility of results being key to the enterprises' ability to detect and correct errors and misconduct. But the increasing volume of research results being produced, coupled with pressure to publish more, fiercer competition for resources and career options and the rise of predatory publishing is leading to a peer review process under pressure and a lack of incentives for spending time trying to reproduce others results or even publish your own negative results. This crisis in science's ability to self-police has been developing against a backdrop of increased fiscal constraint in many developed economies with an attendant requirement for public expenditure to be well justified.

In relation to universities, Ewell (2010) suggests that when assessment is focused too much on accountability, researchers are more likely to be disengaged and this can have an adverse effect on the on-going critical self-examination that is necessary for continuous improvement. However, if universities only focus on improvement they run the risk of having inappropriate, unhelpful or misleading assessment measures imposed on them by outside agencies (Ewell, 2010)

Finding the middle ground between accountability and improvement is not easy, particularly when it comes to publicly funded research. Government programs may be initiated on the basis of encouraging improvement in the performance of some action in society but ultimately they are accountable to treasury and thus to taxpayers, for how the money is spent.

This tension, along with the multi-faceted nature of many research programs suggests that once appropriate indicators have been chosen, they will not necessarily be equal. Decisions need to be made about which indicators actually relate to the ultimate goal of your program – all other indicators should then be discarded as they will only distract from the main activity. This does not mean that data should not be collected in regards to other outputs and outcomes – this provides a way of identifying unintended consequences, both good and bad. But it does mean there has to be a willingness on the part of funders to acknowledge they may need to be flexible in regards some of the indicators that are commonly used for accountability purposes if they get in the way of indicators relating to program success.

### *10.2.1: Cause and Effect – Indicators Driving Behaviours*

Focussing on particular indicators as measures of performance or perceived value is a useful way of influencing individuals and organisations to change their behaviour. When there are financial incentives attached to particular indicators, this effect is more pronounced. In Germany, as bibliometric performance increased in importance for career progression, so too did publication in US-based journals, with their greater impact factors and potential readership leading to potentially greater citation rates (Michels & Schmoch, 2014). As time goes by this may well have implications for researchers undertaking work of highly localised importance. Increasing the importance of international publication in Norwegian reward and funding systems was associated with a shift away from publishing in the grey literature to international journals (Kyvik, 2003). South Korean studies suggest financial incentives targeting both publication quality and quantity are successful in improving both, while promotion requirements based on publication numbers alone are linked with a decrease in quality (Kim & Bak, 2016). Danish studies suggest that if academics consider financial incentives to be a way of management controlling their work, the number of publications may drop, in comparison to an increase if the incentives are considered to be a way of supporting their work (Anderson & Pallesen, 2008). In Australia, the introduction of university-funding formulas including amounts for the number of publications saw the numbers rise, with the greatest increase being in those published in lower quality journals (Butler, 2003). In this case, academics appear to have chosen quantity over quality in response to a financial incentive. It has also been suggested that incentives regarding journal publication in China has resulted in an increase in academic misconduct, manifest in a number of ways (Qiu, 2010). At the very least, these incentives would appear to be hampering the development of a quality scientific publishing sector in China itself (Shao & Shen, 2011).

The latter two examples, in particular, demonstrate why metrics and indicators need to be carefully chosen and defined – they can drive behaviour to change in ways that are not only unexpected, but also undesirable. This is particularly the case when there are financial incentives attached to metrics. Norwegian experience suggests it is possible to link funding to publication activity without negatively affecting quality, but it requires a nuanced model to ensure the Australian experience is not repeated (Schnieder, Aagaard & Bloch, 2016).

When assessments are based on international-data indicators such as journal impact factor and citations they not only will affect the publishing behaviour of researchers, but they may also subtly influence the choices that are made as to where research effort will be directed. In some disciplines, there are open research questions that are highly localised or only relevant at the national level and it thus may be difficult to find an international venue willing to publish results. The pool of potential citers is also likely to be small. When assessments such as promotion are weighted heavily towards these types of indicators, researchers focused on local concerns will likely be disadvantaged and may chose not to pursue important local issues.

It is human nature to respond to incentives and when those incentives are linked to indicators that researchers do not have confidence in, there can be both a personal and a professional cost in attempting reconciliation. Malsch and Tessier (2015) provide an account of the difficulties faced when the journal rankings used for a departmental incentive scheme did not accord with the journals generally perceived to be important for their particular area of research speciality. In this instance they felt that when journal rankings become part of incentive policies it can lead junior researchers to have to deal with contradictory professional and intellectual positions (Malsch & Tessier, 2015). Expressed as a loyalty dilemma, torn between the research field and the academic institution, we must expect these types of situations to affect morale and confidence, with resultant effects on work quality.

Buckeridge and Watts (2013) suggest the rise in using grant income as a performance measure for academics in Australian universities may be effectively driving them to become consultancies, reducing the opportunities to undertake frontier research. In this scenario,

> *"There is now an increased focus on research* means *(ie the obtaining of grants) rather than* ends *(journal publication)."* Buckeridge & Watts (2013).

For journal publications as ends, we could also substitute research impact as outcomes. In many countries, a large portion of funding to support research in universities is distributed primarily through competitive means, with grants awarded for individual projects (typically three to five years long). It has been argued that this approach tends to encourage researchers to focus on short-term, application-driven research due to the uncertainty regarding funding over longer periods and leads to a decrease in groundbreaking, innovative outcomes (Geuna, 2001; Heinze, 2008; Zoller, Zimmerling & Boutellier, 2014). In addition, this funding is usually awarded on the basis of peer review of the proposed research. There have been suggestions that utilising peer review for funding purposes can also lead to less innovative research (for example: Horrobin, 1990; Spier, 2002a; Luukonen, 2012; Lee et al, 2013) due to the challenges in reconciling what Heinze (2008), following on from Polanyi (1958), describes as

> *"… the tension between the plausibility and scientific value of the research on one hand, and its originality and creativity on the other."*

A large part of many peer review examinations of plausibility or feasibility are reliant on the track record of the researchers involved. Applications are usually allocated to discipline-based panels for review. Heinze (2008) reports that successful grantees are usually those who already have a strong record of publications in the area, yet breakthroughs are commonly made by researchers moving into new fields or integrating new fields with their existing areas of expertise. From this he concludes that many of the research funding mechanisms in use are insufficiently flexible to accept that researchers who have made significant achievements in one particular field are capable of broadening their research and moving in to new fields (Heinze, 2008). The increasing emphasis on journal impact factors to assess the performance of individual researchers may also further penalise those who undertake inter-disciplinary research (Rafols, Leydesdorff, O'Hare, Nightingale & Stirling, 2012). Together, these factors may jeopardise the pursuit of impactful outcomes via inter-, multi- and trans-disciplinary research. For researchers and teams working in the new convergence sciences this means that obtaining funding for cross-disciplinary endeavours can be a challenge. Careful thought has to go in to how the application is categorised to ensure it is assessed by the most appropriate panel, but even then, there will usually be large gaps in the expertise of the assessors. In the event they are successful in obtaining funding for this work, they may then find that career progression and recognition becomes problematic.

As we have seen in Chapter 9.1, there is some contradictory evidence regarding the effect of peer review funding allocations on eventual research impact within the academy, as measured by citation counts. Given the fact that in a number of countries researchers may be given very little or no recurrent funding, where

> *"external funding has turned from a source for additional research projects into a necessary contribution to any research a scientist wants to conduct."* (Laudel, 2006).

then we must expect that in a highly competitive environment, researchers will look to maximise their chances of getting that funding. Laudel's (2006) study of Australian and German academic researchers found that in order to gain funding they tend to avoid high-risk research. If this is widespread, it would appear high levels of competition for funding, when coupled with the peer review process, could potentially encourage a culture of timidity – to pass the feasibility test and build track record, proposals will only be submitted if the researcher is very confident of being able to achieve the stated outcomes. In this sense, progress will be incremental. While incremental advancement is a core part of research practice, when it pays off, higher risk research often results in higher impact and thus there is a need to have an optimal balance between low and high risk research. And while some level of competition can lead to increased levels of innovation, Balietti, Goldstone and Helbing (2016) suggest that in highly competitive environments utilising peer review, the behaviour of both those being assessed and those doing the assessment are affected, with increased rejection rates not necessarily resulting in increased quality.

For researchers who have to articulate impact as part of their funding submissions there may be a tension between the need to demonstrate impact and the desire to play it safe in order to secure funding. If there is a disconnect between the factors used to determine if a research activity is funded and the indicators used to assess the success of the activity, what does this mean for researchers attempting to build a track record? The implication is that in order to receive funding they will need to say they will do one thing, but in order to achieve success they may have to do another. In one sense, this may already be happening in some environments – in Australia, successful grants in the 2016 Australian Research Council *Discovery Projects* program were awarded an average of 65% of the funding requested[41]. By necessity in this instance, the delivered research project will be substantially different to that proposed, and may no longer be feasible at all. Is it then fair to assess the success of the research based on the original outcomes sought? Weakening the link between assessment of the proposal and assessment of the outcome by effectively removing the connection between them suggests that assessment ultimately has no viable purpose as a means of accountability in these situations.

What then of the philosophy of undertaking assessment for improvement? As a largely internal function this is likely to be far removed from the types of research impact assessments that are being implemented at national levels. Indeed, it is difficult to visualise an evaluation framework for providing meaningful information to researchers in addition to that which they currently receive as part of the research process. Evaluation at the institutional level and above can be framed in terms of improving the efficiency and efficacy of publicly funded research, but in reality, this is just about holding the sector accountable for the funding they receive. Despite this, impact evaluation can provide valuable feedback to institutions regarding the processes and policies they have in place to encourage impactful research, but as with many factors regarding research impact, these can be areas where researchers have relatively little influence.

Regardless of whether the aim of the assessment is accountability or improvement, chosen indicators do not exist in isolation. They act alongside other metrics and indicators that are applied to individuals and institutions for other purposes to promote a range of behaviours reflecting the values and priorities of those being assessed. The challenge is in ensuring the dominant behaviours are those that you desire.

[41] https://rms.arc.gov.au/RMS/Report/Download/Report/a3f6be6e-33f7-4fb5-98a6-7526aaa184cf/5, accessed 12th May 2016

# Chapter 11: Research Impact Assessment - Conclusion

*"The feasibility of a retrospective evaluation depends on the context and is never guaranteed".*

– Gertler, Martinez, Premand, Rawlings & Vermeersch, Impact Evaluation in Practice (2011)

*"Measuring the impact of R&D activities is the most subjective aspect of assessment and is ill-suited to quantitative measures."*

– National Research Council, Best Practices in Assessment of Research and Development Organisations (2012)

Despite much effort over recent decades, we are still uncertain as to how 'quality research' should be defined. This has not prevented us from implementing attempts to assess it. Quality assessment exercises, whether undertaken at national or individual levels can be based on inputs (for example, number and value of grants received), outputs (for example, number of papers published, PhD students supervised), networks (for example, number of international collaborations) and peer recognition (for example, awards). In some instances, quantitative measures are used as proxies for qualitative: if you have a large number of international collaborations this infers that you and your work are valued by your peers around the world. There can be circular arguments and flawed logic in these inferences. Your international visibility may be just as much due to your being able to resource trips to the most relevant conferences. Your ability to attract quality students may also be dependent on the reputation of your institution. Regardless of this, even the most quantitative of measures is often a reflection of what your peers think. Grant decisions are usually made by peer review panels. Citations are the result of your peers deciding your work has value and contributes to their own. As noted by Weingart (2005)

> *"In fact, publication and citation measures are representations of the communication process as it unfolds in journal publications. Thus, they also embody the peer review evaluations that have led to actual publications. For that very reason they cannot be more exact or objective than peer review judgements".*

The difficulty in defining what is quality research and determining simple, data-driven methods to assess it is a result of the simple fact that quality is a subjective determination and thus always driven by personal values. Ultimately, so too is impact.

Impact assessment is following a similar trajectory to that which the development of quality assessment has followed. We are struggling to find a universal definition of research impact which can be applied across all research disciplines, satisfies all stakeholders and can be measured simply and cost-effectively. Just as with research quality, this universal definition is likely to continue to elude us. But we can select relevant types or aspects of impact to examine for particular research activities.

Despite a lack of consensus around impact, assessment programs are being implemented around the world. For researchers being assessed, there are dangers in these assessments which are different to those navigated in the search for quality.

Just like quality, impact tends to be in the eye of the beholder. But when research quality is assessed, it is generally done so by the research community themselves. Medical researchers have the quality of their work assessed by other medical researchers. Physicists examine other physicists work. Impact assessment, when it is done well, should be undertaken by the wider community. In this way, impact assessment is like determining customer satisfaction. The difficulty for researchers is that, in supply chain terms, they are far removed from the customer. And the further removed from the customer you are, the less influence you have on the actual experience they receive.

To me, this highlights the primary difficulty when using impact as an assessment and decision making tool for research: very few researchers have control over the ability of their work to achieve impact in wider society.

This does not mean we should not examine how research has impact, nor that we should not be encouraging researchers to undertake work that has the potential for wider impact. Researchers are in the business of generating ideas, and without action, ideas remain just that. Who then, is best placed to put ideas into action? This can depend on what the idea relates to and where it has been generated, but traditionally, universities have generated ideas (research) and people who then take those ideas out to the world and implement them (graduates). Publicly funded research organisations may have focused on ideas and partnering with others to implement them, or on just the generation of ideas.

In relation to publicly funded research, if the focus on impact suggests we now believe it is the role of universities to also implement the ideas they generate, then this is a major change. The role of universities in society and the way in which they operate has been the subject of much debate and change in recent decades. Many have been shifting from a collegiate model of operating to a top-down managerial mode. Some governments appear to be shifting from a view of universities as cultural institutions to one of service providers, particularly for economic objectives. Most universities in developed economies would now employ a far greater proportion of non-teaching or non-research staff than they did fifty years ago, reflecting some of these changes.

As an institution, the idea of the modern university reaches back to the establishment of the University of Bologna in the 11$^{th}$ century. It has weathered periods of growth, stagnation and revolution. Many of our most venerable universities are also amongst the oldest, demonstrating that change is possible, and indeed, necessary, to ensure survival. If universities are now required to see their research through to implementation and impact it will require significant investment to support the change, something which is highly unlikely when impact is used itself to determine or justify current funding.

We must ensure we are not punishing (or rewarding) researchers for outcomes over which they have little influence.  This is the greatest challenge for the assessment of research impact going forward.  Not how we assess, but why, what and who.  And, critically, **how** we then make use of those assessments.

## References


Abramo, G, Cicero, T & D'Angelo, CA (2013); *National Peer-Review Research Assessment Exercises for the Hard Sciences Can be a Complete Waste of Money: The Italian Case*; Scientometrics **95**(1): 311-324

Acworth, EB (2008); *University-Industry Engagement: The Formation of the Knowledge Integration Community (KIC) Model at the Cambridge-MIT Institute*; Research Policy **37**(8):1241-1254

Adams, AJ (2015); *Toward Permissionless Innovation in Health Care*; Journal of the American Pharmacists Association **55**(4):359-362

Adams, JD (1990); *Fundamental Stocks of and Productivity Growth*; Journal of Political Economy **98**(4): 673-702

Adie, E (2013); *Gaming Altmetrics*; Altmetric Blog 18 September 2013; available from https://www.altmetric.com/blog/gaming-altmetrics/

Aghion, P, David, PA & Foray, D (2009); *Science, Technology and Innovation for Economic Growth: Linking Policy Research and Practice in 'STIG' Systems*; Research Policy **38**(4):681-693

Agrawal, A & Henderson, R (2002); *Putting Patents in Context: Exploring Knowledge Transfer from MIT*; Management Science **48**(1): 44-60

Agarwal, R, Brown, PJ, Green, R, Randhawa, K & Tan, H (2014); *Management Practices of Australian Manufacturing Firms: Why are Some Firms More Innovative?*; International Journal of Production Research **52**(21): 6496-6517

Ahlgren, P & Waltman, L (2014); *The Correlation Between Citation-Based and Expert-Based Assessments of Publications Channels: SNIP and SJR vs Norwegian Quality Assessments*; Journal of Informetrics **8**(4):985-996

Aksnes, DW (2003); *Characteristics of Highly Cited Papers*; Research Evaluation **12**(3):159-170

Allen Consulting Group (2013); *The Strategic Role of the Australian Automotive Manufacturing Industry Report to the Federal Chamber of Automotive Industries;* available from http://www.acilallen.com.au/cms_files/ACILAllen_FCAI_September2013.pdf

A L (1997); *The High Price of Being World Class*; Science **276**(5314): 904

Al-garadi, MA, Vrathan, KD & Ravana, SD (2016); *Cybercrime Detection in Online Communications: The Experimental Case of Cyberbullying Detection in the Twitter Network*; Computers in Human Behaviour **63**:433-443

Al-Tabbaa, O & Ankrah, S (2016); *Social Capital to Facilitate 'Engineered' University-Industry Collaboration for Technology Transfer: A Dynamic Perspective*; Technological Forecasting and Social Change **104**:1-15

Aldieri, L (2013); *Knowledge Technological Proximity: Evidence from US and European Patents*; Economics of Innovation and New Technology **22**(8): 807-819

Aldieri, L & Cincera, M (2009); *Geographic and Technological R&D Spillover within the Triad: Micro Evidence from US Patents*; The Journal of Technology Transfer **34**(2): 196-211

Altbach, PG, Reisberg, L, & Rumbley, LE (2009); Trends in Global Higher Education: Tracking an Academic Revolution; Report prepared for the UNESCO 2009 World Conference on Higher Education; UNESCO; Paris, France

Altomonte, C, Gamba, S, Mancusi ML & Vezzulli, A (2016); *R&D Investments, Financing Constraints, Exporting and Productivity*; Economics of Innovation and New Technology **25**(3):283-303

Amanatidou, E, Cunningham, P, Gök, A & Garefi, I (2014); *Using Evaluation Research as a Means for Policy Analysis in a 'New' Mission-Oriented Policy Context*; Minerva **52**(4):419-438

Amara, N, Landry, R & Halilem, N (2013); *Faculty Consulting in Natural Sciences and Engineering: Between Formal and Informal Knowledge Transfer*; Higher Education **65**(3):359-384

American Sociological Association (2016); What Counts? Evaluating Public Communication in Tenure and Promotion; Final Report of the ASA Subcommittee on the Evaluation of Social Media and Public Communication in Sociology; available from http://www.asanet.org/sites/default/files/tf_report_what_counts_evaluating_public_communication_in_tenure_and_promotion_final_august_2016.pdf

An, G (2010); *Closing the Scientific Loop: Bridging Correlation and Causality in the Petaflop Age*; Science Translational Medicine **2** (41): 41-44

Andersen, LB & Pallesen, T (2008); *"Not Just for the Money?" How Financial Incentives Affect the Number of Publications at Danish Research Institutions*; International Public Management Journal **11**(1):28-47

Anderson, W (2015); *Peer Review: Maintaining Trust in Research Funding Decisions*; The Medical Journal of Australia **202**(2): 65

Andreassen, HK, Kjekshus, LE & Tjora, A (2015); *Survival of the Project: A Case Study of ICT Innovation in Health Care*; Social Science & Medicine **132**:62-69

Andries, P & Thorwath, S (2014); *Should Firms Outsource their Basic Research? The Impact of Firm Size on In-House versus Outsourced R&D Productivity*; Creativity and Innovation Management **23**(3): 303-317

Ankrah, SN, Burgess, TF, Grimshaw, P & Shaw, NE (2013); *Asking Both University and Industry Actors About Their Engagement in Knowledge Transfer: What Single-Group Studies of Motives Omit*; Technovation **33**(2-3): 50-65

Appleseed (2015); Maryland and Beyond Committed to Our Communities; available from http://web.jhu.edu/administration/gca/EIR%202014/Maryland%20Full%20Report%20EIR%202014.pdf

Archambault, E & Larivière, V (2009); *History of the Journal Impact Factor: Contingencies and Consequences*; Scientometrics **79**(3): 635 – 649

Armingeon, K & Ceka, B (2014); *The Loss of Trust in the European Union During the Great Recession Since 2007: The Role of Heuristics from the National Political System*; European Union Politics **15**(1):82-107

Arora, A, Cohen, WM & Walsh, JP (2016); *The Acquisition and Commercialization of Invention in American Manufacturing: Incidence and Impact*; Research Policy **45**(6):1113-1128

Audretsch, DB (2009); *The Entrepreneurial Society*; Journal of Technology Transfer **34**(3): 245-254

(ATSE) Australian Academy of Technological Sciences and Engineering (2014); Proposal Rewarding Researcher-Industry Engagement and Collaboration: Developing an 'Impact and Engagement for Australia (IEA) Metric; available from http://www.atse.org.au/Documents/reports/impact-engagement-australia-proposal.pdf

Australian Bureau of Statistics (2006); Census of Population and Housing; http://www.abs.gov.au/websitedbs/censushome.nsf/home/tablebuilder?opendocument&navpos=240

Australian Bureau of Statistics (2008) Australian and New Zealand Standard Research Classification (ANZSRC); Catalogue number 1297.0

Australian Bureau of Statistics (2011); Census of Population and Housing http://www.abs.gov.au/websitedbs/censushome.nsf/home/tablebuilder?opendocument&navpos=240

Australian Bureau of Statistics (2015a); Counts of Australian Businesses, including Entries and Exits, June 2010 to June 2014; Catalogue Number 8165.0

Australian Bureau of Statistics (2015b); Selected Characteristics of Australian Business 2013-14; Catalogue Number 8167.0

Australian Bureau of Statistics (2015c); Research and Experimental Development, Businesses, Australia, 2013-14; Catalogue Number 8104.0

Australian Bureau of Statistics (2016); Research and Experimental Development, Government and Private Non-Profit Organisations, Australia, 2014-15; Catalogue Number 8109.0

Australian Research Council (2013a); Linkage Projects Funding Rules for Funding Commencing in 2014; available from www.arc.gov.au

Australian Research Council (2013b); Linkage Infrastructure, Equipment and Facilities Funding Rules for Funding Commencing in 2014; www.arc.gov.au

Australian Research Council (2014); Funding Rules for Schemes Under the Discovery Program for the Years 2014 and 2015; www.arc.gov.au

Australian Research Council (2016); Research Impact Principles and Framework; http://www.arc.gov.au/research-impact-principles-and-framework ; accessed 16th March 2016

Autor, DH, Katz, LF & Kearney, MS (2006); *The Polarization of the US Labor Market*; The American Economic Review **96**(2):189-194

Azoulay, P, Ding, W & Stuart, T (2009); *The Impact of Academic Patenting on the Rate, Quality and Direction of Public Research Output*; The Journal of Industrial Economics **57**(4): 637-676

Baccini, A & De Nicolao, G (2016); *Do They Agree? Bibliometric Evaluation Versus Peer Review in the Italian Research Assessment Exercise*; Scientometrics **108**(3):1651-1671

Bakker, J, Verhoeven, D, Zhang, L & Van Looy, B (2016); *Patent Citation Indicators: One Size Fits All?*; Scientometrics **196**(1):187-211

Balietti, S, Goldstone, RL & Helbing, D (2016); *Peer Review and Competition in the Art Exhibition Game*; Proceedings of the National Academy of Sciences of the United States of America (PNAS) **113**(30):8414-8419

Banal-Estañol, A, Jofre-Bonet, M & Lawson, C (2015); *The Double-Edged Sword of Industry Collaboration: Evidence from Engineering Academics in the UK*; Research Policy **44**(6):1160-1175

Barge-Gil, A & López, A (2015); *R versus D: Estimating the Differentiated Effect of Research and Development on Innovation Results*; Industrial and Corporate Change **24**(1):93-129

Bar-Ilan, J (2008); *Which* h-*index? A Comparison of WoS, Scopus and Google Scholar*; Scientometrics **74**(2): 257-271

Barker, K (2007); *The UK Research Assessment Exercise: Evolution of a National Research Evaluation System*; Research Evaluation **16**(1): 3-12

Bartholomew, RE (2014); *Science for Sale: The Rise of Predatory Journals*; Journal of the Royal Society of Medicine **107**(10):384 - 385

Barnes, C (2015); *The Use of Altmetrics as a Tool for Measuring Research Impact*; Australian Academic & Research Libraries **46**(2):121-134

Basole, RC, Park, H & Barnett, BC (2015); *Coopetition and Convergence in the ICT Ecosystem*; Telecommunications Policy **39**(7)537-552

Bazrafshan, A, Akbar Haghdoost, A & Zare, M (2015); *A Comparison of Downloads, Readership and Citations Data for the Journal of Medical Hypotheses and Ideas*; Journal of Medical Hypotheses and Ideas **9**(1):1-4

Becker, B (2015); *Public R&D Policies and Private R&D Investment: A Survey of the Empirical Evidence*; Journal of Economic Surveys **29**(5):917- 942

Belcher, BM, Rasmussen, KE, Kemshaw, MR & Zornes, DA (2016); *Defining and Assessing Research Quality in a Transdisciplinary Context*; Research Evaluation **25**(1):1-17

Belter, CW (2014); *Measuring the Value of Research Data: A Citation Analysis of Oceanographic Data Sets*; PLoS One **9**(3):e92590

Benos, DJ, Bashari, E, Chaves, JM, Gaggar, A, Kapoor, N, LaFrance, M, Mans, R, Mayhew, D, McGowan, S, Polter, A, Qadri, Y, Sarfare, S, Schultz, K, Splittgerber, R, Stephenson, J, Tower, C, Walton, RG, Zotov, A (2007); *The Ups and Downs of Peer Review*; Advances in Physiology Education; **31**(2):145 – 152

Ben Letaifa, S & Rabeau, Y (2013); *Too Close to Collaborate? How Geographic Proximity Could Impede Entrepreneurship and Innovation*; Journal of Business Research **66**(10): 2071-2078

Bentley, P & Kyvik, S (2011); *Academic Staff and Public Communication: A Survey of Popular Science Publishing Across 13 Countries*; Public Understanding of Science **20**(1):48-63

Berger, F (1982); *The Concept of Absorptive Capacity: Origins, Content and Practical Relevance*; Intereconomics **17**(3): 133-137

Berger, N & Fisher, P (2013); A Well-Educated Workforce is Key to State Prosperity; Economic Analysis and Research Network Report; Economic Policy Institute, Washington USA; Available from http://www.epi.org/publication/states-education-productivity-growth-foundations/

Berger, T & Frey, CB (2015); *Industrial Renewal in the 21st Century: Evidence from US Cities*; Regional Studies **Early Access** DOI: 10.1080/00343404.2015.1100288

Berger, T & Frey, CB (2016); *Did the Computer Revolution Shift the Fortunes of US Cities? Technology Shocks and the Geography of New Jobs*; Regional Science and Urban Economics **57**:38-45

Berman, J (2008); *Connecting with Industry: Bridging the Divide*; Journal of Higher Education Policy and Management **30**(2): 165-174

Bernstein, A (2014); *Abuse and Harassment Diminish Free Speech*; Pace Law Review **35**(1):1-28

Bertrand, O & Mol, MJ (2013); *The Antecedents and Innovation Effects of Domestic and Offshore R&D Outsourcing: The Contingent Impact of Cognitive Distance and Absorptive Capacity*; Strategic Management Journal **34**(6): 751-760

Bessen, J & Meurer, MJ (2008); Patent Failure: How Judges, Bureaucrats and Lawyers Put Innovators at Risk; Princeton University Press; Princeton, USA; ISBN: 9781400828692

Bhattacharya, M (2014); *Business Growth, Size and Age: Evidence from the Business Longitudinal Survey (BLS) Data in Australia*; Australian Economic Papers **53**(3/4): 129 – 138

Binelli, C & Maffioli, A (2007); *A Micro-Econometric Analysis of Public Support to Private R&D in Argentina*; International Review of Applied Economics **21**(3):339-359

Birrell, B (2015); *Too Few or Perhaps Too Many STEM Graduates*; Australian Universities' Review **57**(2): 71-78

Bishop, PR, Schuyler, WH, Ownley, BH, Richards, JK, & Skolits, GJ (2014); *Impacts of an Interdisciplinary Research Centre on Participant Publications and Collaboration Patterns: A Case Study of the National Institute for Mathematical and Biological Synthesis*; Research Evaluation **23**(4): 327-340

Bishop, S, Kavanagh, K & Palit, M (2010); *The Role of Performing Arts Centers: A Case for the City University of New York*; International Journal of Learning **17**(8):473-484

Blanco, LR, Gu, J & Prieger, JE (2016); *The Impact of Research and Development on Economic Growth and Productivity in the US States*; Southern Economic Journal **82**(3):914-934

Bleske-Rechek, A, Morrison, KM & Heidtke, LD (2015); *Causal Inference from Descriptions of Experimental and Non-Experimental Research: Public Understanding of Correlation-Versus-Causation*; The Journal of General Psychology **142**(1):48-70

Bloch, C, Sørenson, MP, Graversen, EK, Schneider, JW, Kalpazidou Schmidt, E, Aagaard, K & Mejlgaard, N (2014); *Developing a Methodology to Assess the Impact of Research Grant Funding: A Mixed Methods Approach*; Evaluation and Program Planning **43**(1): 105-117

Bloch, H & Bhattacharya, M (2016); *Promotion of Innovation and Job Growth in Small- and Medium-Sized Enterprises in Australia: Evidence and Policy Issues*; The Australian Economic Review **49**(2):192-199

Bloom, N, Dorgan, S, Dowdy, J & Van Reenen, J (2007); Management Practice & Productivity: Why They Matter; available from http://cep.lse.ac.uk/management/Management_Practice_and_Productivity.pdf

Bloom, N, Genakos, C, Sadun, R & Van Reenen, J (2012); *Management Practices Across Firms and Countries*; Academy of Management Perspectives **26**(1): 12- 33

Bloom, N & Van Reenen, J (2007); *Measuring and Explaining Management Practices Across Firms and Countries*; Quarterly Journal of Economics **122**(4):1351-1408

Bohannon, J (2013); *Who's Afraid of Peer Review?*; Science **342**(6154): 60-65

Bornmann, L (2012); *Measuring the Societal Impact of Research*; EMBO Reports **13**(8):673-679

Bornmann, L (2013); *What is Societal Impact of Research and How Can it Be Assessed? A Literature Survey*; Journal of the American Society for Information Science and Technology **64**(2): 217 – 233

Bornmann, L (2015); *Alternative Metrics in Scientometrics: A Meta-Analysis of Research into Three Altmetrics*; Scientometrics **103**(3):1123-1144

Bornmann, L (2015a); *Usefulness of Altmetrics for Measuring the Broader Impact of Research*; Aslib Journal of Information Management **67**(3):320-336

Bornmann, L (2015b); *Interrater Reliability and Convergent Validity of F1000Prime Peer Review*; Journal of the Association for Information Science and Technology **66**(12):2415-2426

Bornmann, L (2016); *Measuring Impact in Research Evaluations: A Thorough Discussion of Methods for, Effects of and Problems with Impact Measurements*; Higher Education **First Online** doi:10.1007/s10734-016-9995-x

Bornmann, L & Haunschild, R (2015); *Which People Use Which Scientific Papers? An Evaluation of Data from F1000 and Mendeley*; Journal of Informetrics **9**(3):477-487

Bornmann, L, de Moya Anegón, F, & Leydesdorff, L (2010); *Do Scientific Advancements Lean on the Shoulders of Giants? A Bibliometric Investigation of the Ortega Hypothesis*; PLoS ONE **5**(10); e13327

Bornmann, L & Marx, W (2014); *How Should the Societal Impact of a Piece of Research be Generated and Measured? A Proposal for a Simple and Practicable Approach to Allow Interdisciplinary Comparison;* Scientometrics **98**(1): 211 – 219

Bornmann, L & Marx, W (2015); *Methods for the Generalization of Normalized Citation Impact Scores in Bibliometrics: Which Method Best Reflects the Judgements of Experts?*; Journal of Informetrics **9**(2): 408-418

Bouabid, H (2011); *Revisiting Citation Aging: A Model for Citation Distribution and Life-Cycle Prediction*; Scientometrics **88**(1): 199-211

Bowman, JD (2014); *Predatory Publishing, Questionable Peer Review, and Fraudulent Conferences*; American Journal of Pharmaceutical Education **78**(10): art. 176

Boyack, KW (2004); *Mapping Knowledge Domains: Characterizing PNAS*; Proceedings of the National Academy of Sciences of the United States of America (PNAS) **101**(Suppl 1): 5192-5199

Bozeman, B & Boardman, C (2009); *Broad Impacts and Narrow Perspectives: Passing the Buck on Science and Social Impacts*; Social Epistemology **23**(3-4): 183-198

Bozeman, B & Youtie, J (2016); *Trouble in Paradise: Problems in Academic Research Co-Authoring*; Science and Engineering Ethics **22**(6):1717-1743

Brand, A, Allen, L, Altman, M, Hlava, M & Scott, J (2015); *Beyond Authorship: Attribution, Contribution, Collaboration and Credit*; Learned Publishing **28**(2):151-155

Braun, D & Guston, DH (2003); *Principal-Agent Theory and Research Policy: An Introduction*; Science and Public Policy **30**(5):302-308

Brizan, DG, Gallagher, K, Jahangir, A & Brown, T (2016); *Predicting Citation Patterns: Defining and Determining Influence*; Scientometrics **108**(1):183-200

Broström, A (2012); *Firms' Rationales for Interaction with Research Universities and the Principles of Public Co-Funding*; Journal of Technology Transfer **37**(3):313-329

Bruce, D & Deskins, J (2012); *Can State Tax Policies Be Used to Promote Entrepreneurial Activity?*; Small Business Economics **38**(4): 375-397

Brulin, G & Svensson, L (2011); Managing Sustainable Development Programmes: A Learning Approach to Change; Gower Publishing, Farnham, England; ISBN: 9781409437208

Brulin, G, Svensson, L & Johansson, C (2012); *Policy Programmes to Promote Entrepreneurship and Innovation: A Study of the State of the Art, Design and Impact Issues*; Journal of Strategic Innovation and Sustainability **8**(1): 36 – 45

Bruneel, J, D'Este, P & Salter, A (2010); *Investigating the Factors that Diminish the Barriers to University-Industry Collaboration*; Research Policy **39**(7):858-868

Bstieler, L, Hemmert, M & Barczak, G (2015); *Trust Formation in University-Industry Collaborations in the US Biotechnology Industry: IP Policies, Shared Governance, and Champions*; Journal of Product Innovation Management **32**(1): 111-121

Bucar, M & Rojec, M (2015); *Science-Industry Cooperation in Slovenia: Determinants of Success*; Economic and Business Review **16**(3):315-336

Buckeridge, JS & Watts, R (2013); *On Ethics, the Pursuit of Knowledge, Truth and Status in the Hallowed Halls of Academe*; Integrative Zoology **8**(3):223-31

Butler, L (2003); *Modifying Publication Practices in Response to Funding Formulas*; Research Evaluation **12**(1): 39-46

Butler, L (2003a); *Explaining Australia's Increased Share of ISI Publications – The Effects of a Funding Formula Based on Publication Counts*; Research Policy **32**(1):143-155

Butler, L (2008); *ICT Assessment: Moving Beyond Journal Outputs*; Scientometrics **74**(1):39-55

Butler, L & McAllister, I (2009); *Metrics or Peer Review? Evaluating the 2001 UK Research Assessment Exercise in Political Science*; Political Studies Review **7**(1):3-17

Butler, L & McAllister, I (2011); *Evaluating University Research Performance Using Metrics;* European Political Science **10**(1):44-58

Buxton, M (2011); *The Payback of 'Payback': Challenges in Assessing Research Impact*; Research Evaluation **20**(3):259-260

Calcagnini, G, Giombini, G, Liberati, P & Travaglini, G (2016); *A Matching Model of University-Industry Collaborations*; Small Business Economics **46**(1):31-43

Callinan, M & Gray, A (2015); Defence Science and Innovation An Affordable Strategic Advantage; Australian Strategic Policy Institute Special Report 79; available from https://www.aspi.org.au/publications/defence-science-and-innovation-an-affordable-strategic-advantage

Calver, M, Lilith, M & Dickman, CR (2013); *A 'Perverse Incentive' from Bibliometrics: Could National Research Assessment Exercises (NRAEs) Restrict Literature Availability for Nature Conservation?*; Scientometrics **95**(1): 243-255

Canadian Academy of Health Sciences (2009); Making an Impact A Preferred Framework and Indicators to Measure Return on Investment in Health Research; Report on the Panel on the Return of Investments in Health Research; ISBN 978-0-9811589-0-7

Cappelen, A, Raknerud, A & Rybalka, M (2012); *The Effects of R&D Tax Credits on Patenting and Innovation*; Research Policy **41**(2): 334-345

Cardona, M, Kretschmer, T & Strobel, T (2013); *ICT and Productivity: Conclusions from the Empirical Literature*; Information Economics and Policy **25**(3):109-125

Carree, M, Malva, AD & Santarelli, E (2014); *The Contribution of Universities to Growth: Empirical Evidence for Italy*; Journal of Technology Transfer **39**(3):393-414

Casadevall, A & Fang, FC (2015); *Impacted Science: Impact is Not Importance*; mBio **6**(5): e01593-15

Castano-Martinez, M-S, Mendez-Picazo, M-T & Galindo-Martin, MA (2015); *Policies to Promote Entrepreneurial Activity and Economic Performance*; Management Decision **53**(9): 2073-2087

Castell, S, Charlton, A, Clemence, M, Pettigrew, N, Pope, S, Quigley, A, Navin Shah, J & Silman, T (2014); Public Attitudes to Science 2014 Main Report; Department for Business Innovation and Skills; available from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/348830/bis-14-p111-public-attitudes-to-science-2014-main.pdf

Centre for International Economics (2015); The Importance of Advanced Physical and Mathematical Sciences to the Australian Economy; Report prepared for the Office of the Chief Scientist and the Australian Academy of Science; Australian Academy of Science; Canberra, Australia; ISBN: 978-0-85847-415-4

Centre for International Economics (2016); The Importance of Advanced Biological Sciences to the Australian Economy; Report prepared for the Office of the Chief Scientist and the Australian Academy of Science; Australian Academy of Science; Canberra, Australia; available from http://www.chiefscientist.gov.au/wp-content/uploads/biology-report_web.pdf

Centre for International Economics (2016a); The Importance of Advanced Physical, Mathematical and Biological Sciences to the Australian Economy; Report prepared for the Office of the Chief Scientist and the Australian Academy of Science; Australian Academy of Science; Canberra, Australia; available from http://www.chiefscientist.gov.au/wp-content/uploads/Synthesis-report.pdf

Center for Strategic Economic Research (2013); Economic Impacts of the University of California, Los Angeles; available from http://www.ucla.edu/economic-impact/pdf/ucla-economic-impact-report-2013.pdf

Chai, S & Shih, W (2016); *Bridging Science and Technology Through Academic-Industry Partnerships*; Research Policy **45**(1):148-158

Chakrabarti, AK & Santoro, MD (2004); *Building Social Capital and Learning Environment in University-Industry Relationships*; International Journal of Learning and Intellectual Capital **1**(1): 19-36

Chakraborty, T, Kumar, S, Goyal, P, Ganguly, N & Mukherjee, A (2015); *On the Categorization of Scientific Citation Profiles in Computer Science*; Communications of the ACM **58**(9):82-90

Chalmers, WS & Isenson, RS (1967); *Project Hindsight A Defense Department Study of the Utility of Research*; Science **156**(3782):1571-1577

Chang, S (2010); Academic Genealogy of Mathematicians; World Scientific, Singapore; ISBN: 978981482291

Chen, S, Arsenault, C & Larivière, V (2015); *Are Top-Cited Papers More Interdisciplinary?* Journal of Informetrics **9**(4):1034-1046

Chen, J-R, Chu, Y-P, Ou, Y-P & Yang, C-H (2015); *R&D Specialization and Manufacturing Productivity Growth: A Cross-Country Study*; Japan and the World Economy **34-35**(May-August): 33-43

Cherney, A, Head, B, Povey, J, Ferguson, M & Boreham, P (2015); *Use of Academic Social Research by Public Officials: Exploring Preferences and Constraints that Impact on Research Use*; Evidence & Policy **11**(2): 169-188

Chesbrough, HW & Van Alstyne, M (2015); *Permissionless Innovation*; Communications of the ACM **58**(8): 24-26

Chin Roemer, R & Borchardt, R (2015); *Issues, Controversies and Opportunities for Altmetrics*; Library Technology Reports **51**(5):20-30

Cho, C, Halford, JT, Hsu, S & Ng, l (2016); *Do Managers Matter for Corporate Innovation?* Journal of Corporate Finance **36**206-229

Chubb, J & Watermeyer, R (2016); *Artifice or Integrity in the Marketization of Research Impact? Investigating the Moral Economy of (Pathways to) Impact Statements within Research Funding Proposals in the UK and Australia*; Studies in Higher Education **Early Access** DOI: 10.1080/03075079.2016.1144182

Cochlear Ltd (2016); Cochlear 2015 Annual Report; available from http://www.cochlear.com/wps/wcm/connect/intl/about/investor/annual-reports

Coenen, L, Moodysson, J & Martin, H (2015); *Path Renewal in Old Industrial Regions: Possibilities and Limitations for Regional Innovation Policy*; Regional Studies **49**(5): 850-865

Cohen, G, Schroeder, J, Newson, R, King, L, Rychetnik, L, Milat, AJ, Bauman, AE, Redman, S & Chapman, S (2015); *Does Health Intervention Research Have Real World Policy and Practice Impacts: Testing a New Impact Assessment Tool*; Health Research Policy and Systems **13**:3

Cohen, WM, Florida, R, Randazzese, L & Walsh, J (1998); *Industry and the Academy: Uneasy Partners in the Cause of Technological Advance*; In Challenges to Research Universities; Ed. Noll, RG; The Brookings Institution; Washington, USA; ISBN: 0-8157-1509-9

Cohen, WM & Levinthal, DA (1990); *Absorptive Capacity: A New Perspective on Learning and Innovation*; Administrative Science Quarterly **35**(1): 128-152

Cohen, WM, Nelson, RR & Walsh, JP (2002); *Links and Impacts: The Influence of Public Research on Industrial R&D*; Management Science **48**(1): 1-23

Collier, A, Gray, BJ & Ahn, MJ (2011); *Enablers and Barriers to University and High Technology SME Partnerships*; Small Enterprise Research **18**(1):2-18

Colyvas, J, Crow, M, Gelijns, A, Mazzoleni, R, Nelson, RR, Rosenberg, N, & Sampat, BN (2002); *How Do University Inventions Get Into Practice?*; Management Science **48**(1): 61-72

Comins, JA (2015); *Data-Mining the Technological Importance of Government-Funded Patents in the Private Sector*; Scientometrics **104**(2):425-435

Commonwealth of Australia (2001); Backing Australia's Ability An Innovation Action Plan for the Future; AusInfo, Canberra Australia; ISSN 0 642 72133 5;

Commonwealth of Australia (2014); Defence Issues Paper A Discussion Paper to Inform the 2015 Defence White Paper; Department of Defence, Canberra Australia; ISBN: 978-0-9925662-0-3

Commonwealth of Australia (2014a); Industry Innovation and Competitiveness Agenda An Action Plan for a Stronger Australia; AusInfo, Canberra Australia; ISBN: 978-1-922098-80-1

Commonwealth of Australia (2015); National Innovation and Science Agenda; Department of the Prime Minister and Cabinet; Canberra, Australia; ISBN: 978-1-925238-17-4

Commonwealth Scientific & Industrial Research Organisation (CSIRO) (2013); Annual Report for 2012-13; CSIRO Publishing, Melbourne, Australia

Conference Board of Canada (2015); Impact of the University of Ottawa; available from http://www.conferenceboard.ca/e-library/abstract.aspx?did=7500

Costas, R, Zahedi, Z & Wouters, P (2015); *Do "Altmetrics" Correlate with Citations? Extensive Comparison of Altmetric Indicators with Citations from a Multidisciplinary Perspective*; Journal of the Association for Information Science & Technology **66**(10):2003-2019

Council of Canadian Academies (2012); Informing Research Choices: Indicators and Judgement; The Expert Panel on Science Performance and Research Funding; ISBN: 978-1-926558-42-3

Cowls, J & Schroeder, R (2015); *Causation, Correlation, and Big Data in Social Science Research*; Policy & Internet **7**(4):447-472

Crespi, G, Garone, LF, Maffioli, A & Melendez, M (2015); *Long-Term Productivity Effects of Public Support to Innovation in Colombia*; Emerging Markets Finance & Trade **51**(1):48-64

Cronin, B & Sugimoto, CR (Eds) (2014); Beyond Bibliometrics Harnessing Multidimensional Indicators of Scholarly Impact; MIT Press; Cambridge USA; ISBN: 978-0-262-02679-6/978-0-262-52551-0

Crosling, G, Nair, M & Vaithiligam (2015); *A Creative Learning Ecosystem, Quality of Education and Innovative Capacity: A Perspective from Higher Education*; Studies in Higher Education **40**(7): 1147-1163

Cunningham, S, Theilacker, M, Gahan, P, Callan, V & Rainnie, A (2016); Skills and Capabilities for Australian Enterprise Innovation; Report for the Australian Council of Learned Academies (ACOLA); ACOLA; Melbourne, Australia; ISBN: 978-0-9943738-3-0

Cusumano, MA, Mylonadis, Y & Rosenbloom, RS (1992); *Strategic Manoeuvring and Mass-Market Dynamics*; Business Review History **66**(1): 51 – 94

Cuthill, M, O'Shea, E, Wilson, B & Viljoen, P (2014); *Universities and the Public Good: A Review of Knowledge Exchange Policy and Related University Practice in Australia*; Australian Universities' Review **56**(2):36-46

Cutler & Co (2008); Venturous Australia Building Strength in Innovation; Review of the National Innovation System commissioned by the Minister for Innovation, Industry, Science and Research; ISBN: 978-0-646-50110-9

Dai, X & Cheng, L (2015); *The Effect of Public Subsidies on Corporate R&D Investment: An Application of the Generalized Propensity Score*; Technological Forecasting & Social Change **90**(B): 410-419

Daim, T, Monalisa, M, Dash, P & Brown, N (2007); *Time Lag Assessment Between Research Funding and Output in Emerging Technologies*; Foresight **9**(4): 33-44

Danthi, N, Wu, CO, Shi, P & Lauer, M (2014); *Percentile Ranking and Citation Impact of a Large Cohort of National Heart, Lung and Blood Institute-Funded Cardiovascular R01 Grants*; Circulation Research**114**(4): 600 - 606

Dang, J & Motohashi, K (2015); *Patent Statistics: A Good Indicator for Innovation in China? Patent Subsidy Program Impacts on Patent Quality*; China Economic Review **35**:137-155

Das, S (2015); *Waiting for Growth: Satyajit Das on Policy Making in the Global Economy*; Late Night Live; Australian Broadcasting Corporation (ABC) Radio National; Broadcast 20th September 2015; http://www.abc.net.au/radionational/programs/latenightlive/waiting-for-growth3asatyajit-das-on-policy-making-in-the-globa/6792030

Davies, JB & Slivinski, A (2015); *Economic Efficiency of Federal Provision of Scientific Information and Support for Science Research in Canada*; Canadian Public Policy **41**(4):332-342

de Bellis, N (2009); Bibliometrics and Citation Analysis From the *Science Citation Index* to Cybermetrics; The Scarecrow Press Inc; Lanham USA; ISBN 0-8108-6713-3

Decker, RS, Wimsatt, L, Trice AG & Konstan, JA (2007); A Profile of Federal-Grant Administrative Burden Among Federal Demonstration Partnership Faculty; A Report of the Faculty Standing Committee of the Federal Demonstration Partnership; available from http://www.iscintelligence.com/archivos_subidos/usfacultyburden_5.pdf

Dedehayir, O & Seppanen, M (2015); *Birth and Expansion of Innovation Ecosystems: A Case Study of Copper Production*; Journal of Technology Management & Innovation **10**(1):145-153

Defazio, D, Lockett, A & Wright, M (2009); *Funding Incentives, Collaborative Dynamics and Scientific Productivity: Evidence from the EU Framework Program*; Research Policy **38**(2):293-305

de Freitas, S, Mayer, I, Arnab, S & Marshall, I (2014); *Industrial and Academic Collaboration: Hybrid Models for Research and Innovation Diffusion*; Journal of Higher Education Policy and Management **36**(1):2-14

Delgado López-Cózar, E, Robinson-García, N & Torres-Salina, D (2015); *The Google Scholar Experiment: How to Index False Papers and Manipulate Bibliometric Indicators*; Journal of the Association for Information Science and Technology **65**(3):446-454

de Jong, S, Barker, K, Cox, D, Sveinsdottir, T, Van den Besselaar, P (2014); *Understanding Societal Impact Through Productive Interactions: ICT Research as a Case*; Research Evaluation **23**(2): 89 – 102

de Jong, SPL, Smit, J & van Drooge, L (2016); *Scientists' Response to Societal Impact Policies: A Policy Paradox*; Science and Public Policy **43**(1):102-114

Deloitte Access Economics (2014); *Australia's STEM Workforce: A Survey of Employers*; Report commissioned by the Office of the Chief Scientist; Canberra; available from http://www.chiefscientist.gov.au/2015/04/occasional-paper-stem-skills-in-the-workforce-what-do-employers-want/

Demicheli, V & Di Pietrantonj, C (2007); *Peer Review for Improving the Quality of Grant Applications*; Cochrane Database of Systematic Reviews; Issue 2: Article # MR000003

Department for Business Innovation and Skills (2015); Business Population Estimates for the UK and Regions; https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/467443/bpe_2015_statistical_release.pdf

Department for Business Innovation and Skills (2015a); Fulfilling Our Potential Teaching Excellence, Social Mobility and Student Choice; ISBN: 9781474124928;

Department for Business Innovation and Skills (2014); The Allocation of Science and Research Funding 2015/16 Investing in World-Class Science and Research; available from https://www.gov.uk/government/organisations/department-for-business-innovation-skills

Department of Education and Training (2003 – 2013); Selected Higher Education Statistics – Student Data; available from https://www.education.gov.au/selected-higher-education-statistics-time-series-data-and-publications

Department of Education and Training (2009); Undergraduate Applications, Offers and Acceptances 2009; available from https://www.education.gov.au/undergraduate-applications-offers-and-acceptances-publications

Department of Education and Training (2016); Selected Higher Education Statistics – 2015 Staff Data 2015 Staff Highest Qualification; available from https://docs.education.gov.au/node/38389

Department of Industry and Science (2015); The Australian Government's 2015-16 Science, Research and Innovation Budget Tables; available from http://www.industry.gov.au/innovation/reportsandstudies/Documents/2015-16ScienceResearchAndInnovationBudgetTables.pdf

Department of Innovation, Industry, Science and Research (2009); Powering Ideas An Innovation Agenda for the 21st Century; Commonwealth of Australia; ISBN: 978-0-642-72584-4

Derrick, GE & Samuel, GN (2016); *The Evaluation Scale: Exploring Decisions About Societal Impact in Peer review Panels*; Minerva **54**(1):75-97

Derrick, GE, Haynes, A, Chapman, S & Hall, WD (2011); *The Association Between Four Citation Metrics and Peer Rankings of Research Influence of Australian Researchers in Six Fields of Public Health*; PLoS ONE **6**(4):e18521

D'Este, P & Patel, P (2007); *University-Industry Linkages in the UK: What are the Factors Underlying the Variety of Interactions with Industry?* Research Policy **36**(9):1295-1313

D'Este, P & Perkmann, M (2011); *Why Do Academics Engage with Industry? The Entrepreneurial University and Individual Motivations;* Journal of Technology Transfer **36**(3): 316 – 339

D'Este, P, Tang, P, Mahdi, Neely, A & Sanchez-Barrioluengo, M (2913); *The Pursuit of Academic Excellence and Business Engagement: Is it Irreconcilable?* Scientometrics **95**(2):481-502

Dietrich, JP (2008); *The Importance of Being First: Position Dependent Citation Rates on arXiv:astro-ph*; Publications of the Astronomical Society of the Pacific **120**(864):224-228

Dietz, JS & Bozeman, B (2005); *Academic Careers, Patents and Productivity: Industry Experience as Scientific and Technical Human Capital*; Research Policy **34**(3):349-367

Ding, WW, Murray, F & Stuart, TE (2006); *Gender Differences in Patenting in the Academic Life Sciences*; Science **313**(5787): 665-667

Dinsmore, A, Allen, L & Dolby, K (2014); *Alternative Perspectives to Impact: The Potential of ALMs and Altmetrics to Inform Funders about Research Impact*; PLoS Biology **12**(11):e1002003

Dodgson, M (2015); *The Government's Focus on Innovation is Too Narrow*; The Conversation; available from https://theconversation.com/the-governments-focus-on-innovation-is-too-narrow-48178

Dodgson, M, Hughes, A, Foster, J & Metcalfe, S (2011); *Systems Thinking, Market Failure, and the Development of Innovation Policy: The Case of Australia*; Research Policy **40**(9):1145-1156

Donovan, C (2008); *The Australian Research Quality Framework: A Live Experiment in Capturing the Social, Economic, Environmental, and Cultural Returns of Publicly Funded Research*; New Directions for Evaluation **118**:47-60

DORA (2012); The San Francisco Declaration on Research Assessment; www.ascb.org/dora/ (accessed 20th September 2015)

Drath, R & Horch, A (2014); *Industrie 4.0: Hit or Hype*; IEEE Industrial Electronics Magazine **8**(2): 56-58

Drew, CH, Pettibone, KG, Owen Finch III, F, Giles, D & Jordan, P (2016); *Automated Research Impact Assessment: A New Bibliometrics Approach*; Scientometrics **106**(3):987-1005

Duchek, S (2015); *Enhancing Absorptive Capacity for Innovation and Change: The Role of Structural Determinants*; Journal of Change Management **15**(2): 142-160

Durlak, JA & DuPre, EP (2008); *Implementation Matters: A Review of Research on the Influence of Implementation on Program Outcomes and the Factors Affecting Implementation*; American Journal of Community Psychology **41**(3-4):327-350

Ebrahim, NA, Salehi, H, Embi, MA, Tanha, FH, Gholizadeh, H & Motahar, SM (2014); *Visibility and Citation Impact*; International Education Studies **7**(4):120-125

The Economist (2003); *Coffee-houses The Internet in a Cup*; The Economist, Dec 18 2003; http://www.economist.com/node/2281736

Etzkowitz, H & Klofsten, M (2005); *The Innovating Region: Toward a Theory of Knowledge-Based Regional Development*; R&D Management **35**(3):243-255

Elnasri, A & Fox, KJ (2014); The Contribution of Research and Innovation to Productivity and Economic Growth; Australian School of Business Research Paper No. 2014 ECON 08; available from http://ssrn.com/abstract=2398732

Engineering & Physical Sciences Research Council (2012) http://www.epsrc.ac.uk/ourportfolio/themes/ict/Pages/default.aspx (accessed 3rd March 2012)

Entner, R (2011); International Comparisons: The Handset Replacement Cycle; available from http://mobilefuture.org/wp-content/uploads/2013/02/mobile-future.publications.handset-replacement-cycle.pdf

European Commission (2012) The 7th Framework Program: Information and Communication Technologies (ICTs) http://ec.europa.eu/research/fp7/index_en.cfm?pg=info (accessed 3rd March 2012)

European Commission (2010); Assessing Europe's University Based Research; Publications Office of the European Union, Luxembourg; ISBN: 978-92-79-14225-3; available from http://ec.europa.eu/research/science-society/document_library/pdf_06/assessing-europe-university-based-research_en.pdf

Ewell, PT (2009); Assessment, Accountability, and Improvement; National Institute for Learning Outcomes Assessment; Occasional Paper # 1; available from http://www.learningoutcomeassessment.org/documents/PeterEwell_008.pdf

Eysenbach, G (2008); *Citation Advantage of Open Access Articles*; PLoS Biology **4**(5):e157

Fabrizio, KR (2009); *Absorptive Capacity and the Search for Innovation*; Research Policy **38**(2):255-267

Fang, F, Steen, R & Casadevall, A (2012); *Misconduct Accounts for the Majority of Retracted Scientific Publications*; Proceedings of the National Academy of Sciences (PNAS) **109**(42): 17028-17033

Farla, K & Simmonds, P (2015); REF Accountability Review: Costs, Benefits and Burden; Report by Technopolis to the Four UK Higher Education Funding Bodies; available from http://www.hefce.ac.uk/pubs/rereports/Year/2015/refreviewcosts/Title,104406,en.html

Feller, I, Ailes, CP, & Roessner, JD (2002); *Impacts of Research Universities on Technological Innovation in Industry: Evidence from Engineering Research Centres*; Research Policy **31**(3): 457 – 474

Fenner, M (2013); *What Can Article-Level Metrics Do for You?* PLoS Biology **11**(10):e1001687

Ferguson, G (2010); Risks and Rewards: Defence R&D in Australia; Australian Strategic Policy Institute (ASPI) Policy Analysis # 71; available from https://www.aspi.org.au/publications/risks-and-rewards-defence-r-and-d-in-australia-by-gregor-ferguson/11_35_29_AM_Policy_Analysis71_defence_R-and-D.pdf

Florence, AT (2015); *Cited But Not Read and Read But Not Cited*; International Journal of Pharmaceutics **492**(1-2):264-265

Finardi, U (2013); *Correlation between Journal Impact Factor and Citation Performance: An Experimental Study*; Journal of Informetrics **7**(2):357-370

Fini, R, Lacetera, N & Shane, S (2010); *Inside or Outside the IP System? Business Creation in Academia*; Research Policy **39**(8):1060-1069

Fisch, CO, Hassel, TM, Sandner, PG & Block, JH (2015); *University Patenting: A Comparison of 300 Leading Universities Worldwide*; The Journal of Technology Transfer **40**(2):318-345

Fisher, DK & Gould, PJ (2012); *Open-Source Hardware is a Low-Cost Alternative for Scientific Instrumentation and Research*; Modern Instrumentation **1**(2):8-20

Franceschini, F, Maisano, D & Mastrogiacomo, L (2015); *Influence of Omitted Citations on the Bibliometric Statistics of the Major Manufacturing Journals*; Scientometrics **103**(3):1083-1122

Franceschet, M (2010); *A Comparison of Bibliometric Indicators for Computer Science Scholars and Journals on Web of Science and Google Scholar*; Scientometrics **83**(1): 243-258

Franco, M & Haase,H (2015); *University-Industry Cooperation: Researchers' Motivations and Interaction Channels*; Journal of Engineering and Technology Management **36**(April-June): 41-51

Fransman, M (2014); Models of Innovation in Global ICT Firms: The Emerging Global Innovation Ecosystems; JCR Scientific and Policy Reports – EUR 26771 EN. Seville: JRC-IPTS; available from http://bookshop.europa.eu/en/models-of-innovation-in-global-ict-firms-pbLFNA26774/?CatalogCategoryID=CXoKABst5TsAAAEjepEY4e5L

Freyne, J, Coyle, L, Smyth, B & Cunningham, P (2010); *Relative Status of Journal and Conference Publications in Computer Science*; Communications of the ACM **53**(11): 124-132

Frietsch, R, Neuhäusler, P, Jung, T & Van Looy, B (2014); *Patent Indicators for Macroeconomic Growth – The Value of Patents Estimated by Export Volume*; Technovation **34**(9):546-558

Fung, KC, Aminian, N & Tung, CY (2016); *Some Characteristics of Innovation Activities: Silicon Valley, California, China and Taiwan*; Economic Change and Restructuring **49**(2):221-240

Gallo, SA, Carpenter, AS, Irwin, D, McPartland, CD, Travis, J, Reynders, S, Thompson, LA & Glisson, SR (2014); *The Validation of Peer Review through Research Impact Measures and the Implications for Funding Strategies*; PLoS ONE **9**(9): e106474

Gardiner, B, Mansfield, M, Anderson, I, Holder, J Louter, D & Ulmanu, M (2016); *The Dark Side of Guardian Comments*; The Guardian Online; Tues 12th April; https://www.theguardian.com/technology/2016/apr/12/the-dark-side-of-guardian-comments

Garner, JG, Porter, AL, Newman, NC & Crowl, TA (2012); *Assessing Research Network and Disciplinary Engagement Changes Induced by an NSF Program*; Research Evaluation; **21**(2): 89-104

Gastwirth, JL (2013); *Should Law and Public Policy Adopt 'Practical Causality' as the Appropriate Criteria for Deciding Product Liability Cases and Public Policy?*; Law, Probability and Risk **12**(3/4):169-188

Geroski, PA & Machin, S (1993); *Innovation, Profitability and Growth Over the Business Cycle*; Empirica **20**(1):35-50

Gertler, PJ, Martinez, S, Premand, P, Rawlings, LB & Vermeersch, CMJ (2011); Impact Evaluation in Practice; The World Bank; Washington DC, USA; ISBN: 978-0-8213-8541-8

Gertner, D, Roberts, J & Charles, D (2011); *University-Industry Collaboration: A CoPs Approach to KTPs;* Journal of Knowledge Management **15**(4): 625-647

Geuna, A (2001); *The Changing Rationale for European University Research Funding: Are There Negative Unintended Consequences?*; Journal of Economic Issues **35**(3):607-632

Geuna, A & Nesta, L (2006); *University Patenting and its Effect on Academic Research: The Emerging European Evidence*; Research Policy **35**:843-863

Geuna, A & Rossi, F (2015); *The Economic Role and Impact of University Research*; in The University and the Economy Pathways to Growth and Economic Development; Eds: Geuna, A & Rossi, F; Edward Elgar Publishing; Cheltenham, United Kingdom; ISBN: 978 178 254 9482

Gilman, M & Serbanica, C (2014); *University-Industry Linkages in the UK: Emerging Themes and 'Unanswered' Questions*; Prometheus **32**(4):403-439

Gingras, Y (2014); *Criteria for Evaluating Indicators*; In Cronin, B & Sugimoto, CR (eds); Beyond Bibliometrics Harnessing Multidimensional Indicators of Scholarly Impact; MIT Press, Cambridge USA; ISBN: 978-0-262-02679-6/978-0-262-52551-0; pp 109 – 125

Gobble, MAM (2015); *Regulating Innovation in the New Economy*; Research Technology Management **58**(2):62-64

Gobble, MAM (2014); *Charting the Innovation Ecosystem*; Research Technology Management **57**(4):55-57

Godin, B & Gingras, Y (2000); *Impact of Collaborative Research on Academic Science*; Science and Public Policy **27**(1): 65-73

Godoy, D, Zunino, A & Mateos, C (2015); *Publication Practices in the Argentinian Computer Science Community: A Bibliometric Perspective*; Scientometrics **102**(2):1795-1814

Gök, A & Edler, J (2012); *The Use of Behavioural Additionality Evaluation in Innovation Policy Making*; Research Evaluation **21**(4):306-318

Gooch, D, Vasalou, A & Benton, L (2016); *Impact in Interdisciplinary and Cross-Sector Research: Opportunities and Challenges*; Journal of the Association for Information Science and Technology **Early View** DOI:10.1002/asi.23658

Gordon, RJ (2000); *Does the "New Economy" Measure up to the Great Inventions of the Past?*; The Journal of Economic Perspectives **14**(4):49-74

Gordon, R & Poulin, BJ (2009a); *Cost of the NSERC Science Grant Peer Review System Exceeds the Cost of Giving Every Qualified Researcher a Baseline Grant* Accountability in Research **16**(1): 13-40

Gordon, R & Poulin, BJ (2009b); *Indeed: Cost of the NSERC Science Grant Peer Review System Exceeds the Cost of Giving Every Qualified Researcher a Baseline Grant*; Accountability in Research **16**(4): 232-233

Görg, H & Stroble, E (2007); *The Effect of R&D Subsidies on Private R&D*; Economica **74**(294):215-234

Gorodnichenko, Y & Schnitzer, M (2013); *Financial Constraints and Innovation: Why Poor Countries Don't Catch Up*; Journal of the European Economics Association; **11**(5): 1115-1152

Gorraiz, J, Gumpenberger, C & Schlögl, C (2014); *Usage versus Citation Behaviour in Four Subject Areas*; Scientometrics **101**(2):1077-1095

Graduate Careers Australia (2014); 2013 Postgraduate Destinations Tables and Figures; available from http://www.graduatecareers.com.au/Research/ResearchReports/PostgraduateDestinations

Graduate Careers Australia (2015); Australian Graduate Survey; *http://www.graduatecareers.com.au/research/surveys/australiangraduatesurvey/* accessed 3rd July 2015

Green, R, Agarwal, R, Van Reenen, J, Bloom, N, Homkes, R, Samson, D, Matthews, J, Gollan, P, Buchanan, J, Toner, P & Boedker, C (2009); Management Matters in Australia: Just How Productive Are We? Findings from the Australian Management Practices and Productivity Global Benchmarking Project; Report Commissioned for the Department of Innovation, Industry, Science and Research, Government of Australia; ISBN 978 0 642 72626 1

Greenhalgh, T & Fahy, N (2015); *Research Impact in the Community-Based Health Sciences: an Analysis of 162 Case Studies from the 2014 UK Research Excellence Framework*; BMC Medicine **13**:232

Greenwood, DC (2007); *Reliability of Journal Impact Factor Rankings*; BMC Medical Research Methodology **7**:48

Grimm, HM & Jaenicke, J (2015); *Testing the Causal Relationship Between Academic Patenting and Scientific Publishing in Germany: Crowding-Out or Reinforcement?*; The Journal of Technology Transfer **40**(3):512-535

Grimpe, C & Hussinger, K (2013); *Formal and Informal Knowledge and Technology Transfer from Academia to Industry: Complementary Effects and Innovation Performance*; Industry and Innovation **20**(8): 683 – 700

Grimpe, C & Kaiser, U (2010); *Balancing Internal and External Knowledge Acquisition: The Gains and Pains from R&D Outsourcing*; Journal of Management Studies **47**(8): 1483-1509

Groff, K, Bachli, E, Lansdowne, M & Capaldo, T (2014); *Review of Evidence of Environmental Impacts of Animal Research Testing*; Environments **1**(1):14-30

Grose, TK (2006); *Challenging Matchup*; ASEE Prism **15**(6):18-23

Group of Eight (2013); The Changing PhD Discussion Paper; available from https://go8.edu.au/sites/default/files/docs/the-changing-phd_final.pdf

Grove, J (2012); *Proportion of Academics with PhDs, 2012*; Times Higher Education 1 November 2012; https://www.timeshighereducation.com/news/proportion-of-academics-with-phds-2012/421657.article

Grundfest, WS, Lai, E, Peterson, CM & Friedl, KE (2012); *Promoting Innovation and Convergence in Military Medicine: Technology-Inspired Problem Solving*; IEEE Circuits and Systems Magazine **12**(3):14-29

Gulbransden, M & Smeby, JC (2005); *Industry Funding and University Professors' Research Performance*; Research Policy **34**:932-950

Gunasekara, C (2006); *Dilemmas in Regional University-Industry Research Collaboration*; Local Economy **21**(2):166-179

Guthrie, B & Bryant, G (2014); Postgraduate Destinations 2013 A Report on the Work and Study Outcomes of Recent Higher Education Postgraduates; Graduate Careers Australia Ltd, Melbourne, Australia; ISSN: 1322-9311

Haddow, G (2015): *Research Classification and the Social Sciences and Humanities in Australia: (Mis)Matching Organizational Unit Contribution and the Impact of Collaboration*; Research Evaluation **24**(4): 325-339

Hafner, K & Lyon, M (1996); Where Wizards Stay Up Late (The Origins of the Internet); Touchstone; New York , USA; ISBN: 0-684-87216-1

Hajli, M, Sims, JM & Ibragimov, V (2015); *Information Technology (IT) Productivity Paradox in the 21st Century*; International Journal of Productivity and Performance Management **64**(4):457-478

Hall, LA & Bagchi-Sen, S (2002); *A Study of R&D, Innovation, and Business Performance in the Canadian Biotechnology Industry*; Technovation **22**(4): 231-244

Hanney, SR, Castle-Clarke, S, Grant, J, Guthrie, S, Henshall, C, Mestre-Ferrandiz, J, Pistollato, M, Pollitt, A, Sussex, J & Wooding, S (2015); *How Long Does Biomedical Research Take? Studying the Time Taken Between Biomedical and Health Research and its Translation into Products, Policy, and Practice*; Health Research Policy & Systems **13**(1): 1 – 32

Hardaker, C & McGlashan, M (2016); *"Real Men Don't Hate Women": Twitter Rape Threats and Group Identity*; Journal of Pragmatics **91**:80-93

Hardy, GH (1940); A Mathematician's Apology; Cambridge University Press

Harhoff, D, Henkel, J & von Hippel, E (2003); *Profiting from Voluntary Information Spillovers: How Users Benefit by Freely Revealing their Innovations*; Research Policy **32**(10):1753-1769

Harzing, A-W & Alakangas, S (2016); *Google Scholar, Scopus and the Web of Science: A Longitudinal and Cross-Disciplinary Comparison*; Scientometrics **106**(2):787-804

Haskel, J & Wallis, G (2013); *Public Support for Innovation, Intangible Investment and Productivity Growth in the UK Market Sector*; Economics Letters **119**(2): 195 – 198

Haupt, R (2006); *The Industry-University Intellectual Property Paradox*; IEEE Antennas and Propagation Magazine; **48**(2):134-136

Haustein, S, Costas, R & Larivière, V (2015); *Characterizing Social Media Metrics of Scholarly Papers: The Effect of Document Properties and Collaboration Patterns*; PLoS ONE **10**(3):e0120495

Haynes, AS, Gillespie, JA, Derrick, GE, Hall, WD, Redman, S, Chapman, S & Sturk, H (2011); *Galvanizers, Guides, Champions, and Shields: The Many Ways that Policymakers use Public Health Researchers*; The Milbank Quarterly **89**(4): 564-598

Head, BW (2015); *Relationships between Policy Academics and Public Servants: Learning at a Distance?*; Australian Journal of Public Administration **74**(1):5-12

Heinze, T (2008); *How to Sponsor Ground-Breaking Research: A Comparison of Funding Schemes*; Science and Public Policy **35**(5):302-318

Helgi Analytics; Helgi Library online database; http://www.helgilibrary.com/pages/data

Hemmert, M, Bstelier, L & Okamuro, H (2014); *Bridging the Cultural Divide: Trust Formation in University-Industry Research Collaborations in the US, Japan and South Korea*; Technovation **34**(10): 605-616

Henderson, R (2013); *Industry Employment and Output Projections to 2022*; Monthly Labor Review December 2013; Bureau of Labor Statistics; available from http://www.bls.gov/opub/mlr/2013/article/industry-employment-and-output-projections-to-2022-1.htm

Herbert, DL, Barnett, AG, Clarke, P & Graves, N (2013); *On the Time Spent Preparing Grant Proposals: an Observational Study of Australian Researchers*; BMJ Open **3**: e002800

Herbert, DL, Coveney, J, Clarke, P, Graves, N & Barnett, AG (2014); *The Impact of Funding Deadlines on Personal Workloads, Stress and Family Relationships: a Qualitative Study of Australian Researchers*; BMJ Open **4**: e004462

(HEFCE ) Higher Education Funding Council for England (2015); The Metric Tide: Correlation Analysis of REF 2014 Scores and Metrics (Supplementary Report II to the Independent Review of the Role of Metrics in Research Assessment and Management; HEFCE; ISBN: 1902369297

(HEFCE )Higher Education Funding Council for England (2015a); The Nature, Scale and Beneficiaries of Research Impact An Initial Analysis of Research Excellence Framework (REF) 2014 Impact Case Studies Underlying Data for Impact Topics; available from http://www.hefce.ac.uk/pubs/rereports/Year/2015/analysisREFimpact/

(HEFCE )Higher Education Funding Council for England (2015b); Higher Education – Business and Community Interaction Survey 2013 – 2014 ; Report on Survey; Ref: 2015/13; available from http://www.hefce.ac.uk/media/HEFCE,2014/Content/Pubs/2015/201513/2015-13.pdf

Hill, CT (2007); *The Post-Scientific Society*; Issues in Science and Technology **24**(1):78-85

Hoffmann, CP, Lutz, C & Meckel, M (2016); *A Relational Altmetric? Network Centrality on ResearchGate as an Indicator of Scientific Impact*; Journal of the Association for Information Science and Technology **67**(4):765-775

Holbrook, JB & Frodeman, R (2011); *Peer Review and the ex ante Assessment of Societal Impacts*; Research Evaluation **20**(3): 239 – 246; September 2011

Holt, GD, Goulding, JS & Akintoye, A (20I6); *Enablers, Challenges and Relationships between Research Impact and Theory Generation*; Engineering, Construction and Architectural Management **23**(1):20-39

Hong, J, Hong, S, Wang, L, Xu, Y & Zhao, D (2015); *Government Grants, Private R&D Funding and Innovation Efficiency in Transition Economy*; Technology Analysis & Strategic Management **27**(9):1068-1096

Horrobin, DF (1990); *The Philosophical Basis of Peer Review and the Suppression of Innovation*; Journal of the American Medical Association (JAMA) **263**(10):1438-1441

House of Commons Science and Technology Committee (2011); Peer Review in Scientific Publications; Eighth Report of Session 2010-12; HC 856; The Stationery Office; London, United Kingdom; available from http://www.parliament.uk/business/committees/committees-a-z/commons-select/science-and-technology-committee/inquiries/peer-review/

Howison, J & Bullard, J (2015); *Software in the Scientific Literature: Problems with Seeing, Finding, and Using Software Mentioned in the Biology Literature*; Journal of the Association for Information Science and Technology **67**(9):2137-2155

Howison, J, Deelman, E, McLennan, MJ, da Silva, RF & Herbsleb, JD (2016); *Understanding the Scientific Software Ecosystem and its Impact: Current and Future Measures*; Research Evaluation **24**(4):454-470

Hsu, F- M & Hsueh, C-C (2009); *Measuring Relative Efficiency of Government-Sponsored R&D Projects: A Three-Stage Approach*; Evaluation and Program Planning **32**(2):178-186

Hud, M & Hussinger, K (2015); *The Impact of R&D Subsidies During the Crisis*; Research Policy **44**(10):1844-1855

Hughes, A & Kitson, M (2012); *Pathways to Impact and the Strategic Role of Universities: New Evidence on the Breadth and Depth of University Knowledge Exchange in the UK and the Factors Constraining its Development*; Cambridge Journal of Economics **36**(3):723-750

IBM (2005); IBM Statement of Non-Assertion of Named Patents Against OSS; available from http://www.ibm.com/ibm/licensing/patents/pledgedpatents.pdf

IBM (2011); IBM Opens Research and Development Laboratory in Australia; https://www-03.ibm.com/press/au/en/pressrelease/35671.wss accessed 3rd July 2015

Ioannidis, JPA, Boyack, KW & Klavans, R (2014); *Estimates of the Continuously Publishing Core in the Scientific Workforce*; PLoS ONE **9**(7): e101698;

Innvaer, S, Vist, G, Trommald, M & Oxman, A (2002); *Health Policy-Makers' Perceptions of Their Use of Evidence: A Systematic Review*; Journal of Health Services Research & Policy **7**(4): 239-244

Iselid, YGL (2008); Web of Science *and* Scopus*: A Journal Title Overlap Study*; Online Information Review **32**(1): 8-21

Jackson, D (2014); *Personality Traits in Australian Business Graduates and Implications for Organizational Effectiveness*; Industry & Higher Education **28**(2):113-126

Jacobellis v Ohio (1964); United States Reports; **378** US 184(1964); Supreme Court of the United States

Jacso, P (2005); *As We May Search – Comparison of Major Features of the* Web of Science, Scopus *and* Google Scholar *Citation-Based and Citation-Enhanced Databases*; Current Science **89**(9): 1537-1547

Jensen, P, Rouquier, J-B, Kreimer, P & Croissant, Y (2008); *Scientists Who Engage with Society Perform Better Academically*; Science and Public Policy **35**(7):527-541

Johnson, S (2010); Where Good Ideas Come From The Natural History of Innovation; Riverhead Books; New York, USA; ISBN: 978-1-59448-771-2

Joly, P-B, Gaunand, A, Colinet, L, Larédo, P, Lemarié, S & Matt, M (2015); *ASIRPA: A Comprehensive Theory-Based Approach to Assessing the Societal Impacts of a Research Organization*; Research Evaluation **24**(4):440-453

Jonsson, L , Baraldi, E, Larsson, L-E, Forsberg, P & Severinsson,K (2015); *Targeting Academic Engagement in Open Innovation: Tools, Effects and Challenges for University Management*; Journal of the Knowledge Economy **6**(3): 522-550

Jubb, M (2016); *Peer Review: The Current Landscape and Future Trends*; Learned Publishing **29**(1):13-21

Jung, HJ & Lee, J (2014); *The Impacts of Science and Technology Policy Interventions on University Research: Evidence from the US National Nanotechnology Initiative*; Research Policy **43**(1):74-91

Jung, K & Andrew, S (2014); *Building R&D Collaboration between University-Research Institutes and Small Medium-Sized Enterprises*; International Journal of Social Economics **41**(12): 1174 – 1193

Kakuk, P (2009); *The Legacy of the Hwang Case: Research Misconduct in Biosciences*; Science and Engineering Ethics **15**(4):545-562

Kamenetzky, JR (2013); *Opportunities for Impact: Statistical Analysis of the National Science Foundation's Broader Impacts Criterion*; Science and Public Policy **40**(1): 72 – 84; July 2013

Kaspura, A (2011); The Engineering Profession: A Statistical Overview 8th Edition; Engineers Australia; Canberra, Australia; ISBN: 978 0 85825 894 5

Kaspura, A (2014); The Engineering Profession: A Statistical Overview 11th Edition; Engineers Australia; Canberra, Australia; ISBN: 978 1 922107 20 6

Ke, Q, Ferrara, E, Radicchi, F & Flammini, A (2015); *Defining and Identifying Sleeping Beauties in Science*; Proceedings of the National Academy of Sciences of the United States of Australia (PNAS) **112**(24):7426-7431

Kennedy, J, Lyons, T & Quinn, F (2014); *The Continuing Decline of Science and Mathematics Enrolments in Australian High Schools*; Teaching Science; **60**(2):34 - 47

Kesselheim, AS, Cook-Deegan, RM, Winickoff, DE & Mello, MM (2013); *Gene Patenting – The Supreme Court Finally Speaks*; New England Journal of Medicine **369**(9):869-875

Kim, DH & Bak, H-J (2016); *How Do Scientists Respond to Performance-Based Incentives? Evidence from South Korea*; International Public Management Journal **19**(1): 31-52

King, C (2012); *Multiauthor Papers: Onward and Upward*; ScienceWatch Newsletter July 2012; http://archive.sciencewatch.com/newsletter/2012/201207/multiauthor_papers/

King's College London and Digital Science (2015); The Nature, Scale and Beneficiaries of Research Impact: An Initial Analysis of Research Excellence Framework (REF) 2014 Impact Case Studies; Bristol, United Kingdom, HEFCE; available from http://www.kcl.ac.uk/sspp/policy-institute/publications/Analysis-of-REF-impact.pdf

Kobayashi, H (2015); *Academic Genealogy of Shoshichi Kobayashi and Individuals Who Influenced Him*; in Geometry and Analysis on Manifolds In Memory of Professor Soshichi Kobayashi; Eds: Ochiai, T, Mabuchi, T, Maeda, Y, Noguchi, J & Weinstein, A; Springer International Publishing; Zurich, Switzerland; ISBN: 978-3-319-11522-1

Koch, A & Strotmann, H (2008); *Absorptive Capacity and Innovation in the Knowledge Intensive Business Service Sector*; Economics of Innovation and New Technology **17**(6): 511-531

Kodumuri, P, Ollivere, B, Holley, J & Moran, CG (2014); *The Impact Factor of a Journal is a Poor Measure of the Clinical Relevance of its Papers*; The Bone & Joint Journal **96-B**:414-419

Kornhaber, RA, McLean, LM & Baber, RJ (2015); *Ongoing Ethical Issues Concerning Authorship in Biomedical Journals: An Integrative Review*; International Journal of Nanomedicine **10**: 4837-4846

Kothari, A, MacLean, L & Edwards, N (2009); *Increasing Capacity for Knowledge Translation: Understanding How Some Researchers Engage Policy Makers*; Evidence & Policy **5**(1): 33-51

Kulage, KM, Schnall, R, Hickey, KT, Travers, J, Zezulinski, K, Torres, F, Burgess, J, Larson, EL & Maxwell, AC (2015); *Time and Costs of Preparing and Submitting an NIH Grant Application at a School of Nursing*; Nursing Outlook **63**(6): 639-649

Kurts, A (2013); *Consequences of the US Supreme Court Decision on Gene Patenting;* Intellectual Property Forum **95**:15-27

Kurtz, MJ, Eichhorn, G, Accomazzi, A, Grant, C, Demleitner, M, Murray, SS, Martimbaeu, N & Elwell, B (2005); *The Bibliometric Properties of Article Readership Information*; Journal of the American Society for Information Science and Technology **56**(2):111-128

Kyvik, S (2003); *Changing Trends in Publishing Behaviour Among University Faculty, 1980 – 2000*; Scientometrics **58**(1): 35-48

Kwon Bae, J (2015); *The Effects of Technological, Organizational, and People Characteristics of Absorptive Capacity and Innovation Performance in IT Industrial Clusters*; International Journal of Multimedia and Ubiquitous Engineering **10**(2): 383-394

Lachance,C, Poirier, S & Larivière, V (2014); *The Kiss of Death? The Effect of Being Cited in a Review on Subsequent Citations*; Journal of the Association for Information Science and Technology **65**(7):1501-1505

Laine, K, Leino, M & Pulkinnen, P (2015); *Open Innovation Between Higher Education and Industry*; Journal of the Knowledge Economy **6**(3):589-610

Lampe, RL & Moser, P (2012); Do Patent Pools Encourage Innovation? Evidence from 20 US Industries Under the New Deal; National Bureau of Economic Research (NBER) Working Paper No. 18316; available from http://www.nber.org/papers/w18316.pdf

Lancet Oncology Editors (2015); *Restoring Confidence in Research Integrity*; The Lancet Oncology **16**(8):871

Larivière, V, Haustein, S & Börner, K (2015): *Long-Distance Interdisciplinarity Leads to Higher Scientific Impact*; PLoS One **10**(3):e0122565

Larivière, V & Gingras, Y (2010); *On the Relationship Between Interdisciplinarity and Scientific Impact*; Journal of the American Society of Information Science and Technology **61**(1):126-131

Laudel, G (2006); *The Art of Getting Funding: How Scientists Adapt to Their Funding Conditions*; Science and Public Policy **33**(7):489-504

Lawson, C & Sterzi, V (2014); *The Role of Early-Career Factors in the Formation of Serial Academic Inventors*; Science and Public Policy **41**(4): 464-479

Lazarsfeld, PF (1958); *Evidence and Inference in Social Research*; Daedalus **87**(4): 99 – 130

Lee, CJ, Sugimoto, CR, Zhang, G & Cronin, B (2012); *Bias in Peer Review*; Journal of the American Society for Information Science and Technology **64**(1):2-17

Lee, N, Sameen, H & Cowling, M (2015); *Access to Finance for Innovative SMEs Since the Financial Crisis*; Research Policy **44**(2): 370-380

Lewison, G & Dawson, G (1998); *The Effect of Funding on the Outputs of Biomedical Research*; Scientometrics **41**(1-2): 17-27

Lewison, G & Devey, G (1999); *Bibliometric Methods for the Evaluation of Arthritis Research*; Rheumatology **38**(1): 13 – 20

Leyden, DP & Link, AN (2014); *Research Risk and Public Policy in a Knowledge-Based Economy: the Relative Research Efficiency of Government versus University Labs*; Journal of the Knowledge Economy **5**(2):294-304

Li, D & Agha, L (2015); *Big Names or Big Ideas: Do Peer-Reviewed Panels Select the Best Science Proposals?*; Science **348**(6233): 434-438

Li, X, Thelwall, M & Giustini, D (2012); *Validating Online Reference Managers for Scholarly Impact Measurement*; Scientometrics **91**(2):461-471

Li, Y, Youtie, J & Shapira, P (2015); *Why Do Technology Firms Publish Scientific Papers? The Strategic Use of Science by Small and Midsize Enterprises in Nanotechnology*; Journal of Technology Transfer **40**(6):1016-1033

Li, R, Chambers, T, Ding, Y, Zhang, G & Meng, L (2014); *Patent Citation Analysis: Calculating Science Linkage Based on Citing Motivation*; Journal of the Association for Information Science and Technology **65**(5):1007-1017

Lin, J & Fenner, M (2013); *Altmetrics in Evolution; Defining and Redefining the Ontology of Article-Level Metrics*; Information Standards Quarterly **25**(2):20-26

Loi, M & Rodrigues, M (2012); A Note on the Impact Evaluation of Public Policies: The Counterfactual Analysis; European Commission Joint Research Centre Report No. EUR 25519 EN; Publications Office of the European Union; Luxembourg, Belgium; ISBN: 978-92-79-26425-2

Louis, KS, Jones, LM, Anderson, M, Blumenthal, D, & Campbell, EG (2001); *Entrepreneurship, Secrecy, and Productivity: A Comparison of Clinical and Non-Clinical Life Sciences Faculty*; Journal of Technology Transfer **26**:233-245

Lozano, GA, Larivière, V & Gingras, Y (2012); *The Weakening Relationship Between the Impact Factor and Papers' Citations in the Digital Age*; Journal of the American Society for Information Science and Technology **63**(11):2140-2145

Lundberg, J (2015); *Does Academic Research Affect Local Growth? Empirical Evidence Based on Swedish Data*; Regional Studies **Early Access** 10.1080/00343404.2015.1107182

Luukkonen, T (2000); *Additionality of EU Framework Programmes*; Research Policy **29**(6):711-724

Luukkonen, T (2012); *Conservatism and Risk-taking in Peer Review: Emerging ERC Practices*; Research Evaluation **21**(1):48-60

Macdonald, S (2015); *Emperor's New Clothes: The Reinvention of Peer Review as Myth*; Journal of Management Inquiry **24**(3): 264-279

Mack, J & Wilson, R (2015); Trends in Mathematics and Science Subject Combinations in the NSW HSC 2001 – 2014 by Gender; Working Paper. Available from http://www.maths.usyd.edu.au/u/SMS/MMW2015.pdf

Maflahi, N & Thelwall, M (2016); *When are Readership Counts as Useful as Citation Counts? Scopus versus Medeley for LIS Journals*; Journal of the Association for Information Science & Technology **67**(1):191-199

Magerman, T, Van Looy, B & Debackere, K (2015); *Does Involvement in Patenting Jeopardize One's Academic Footprint? An Analysis of Patent-Paper Pairs in Biotechnology*; Research Policy **44**(9):1702-1713

Malsch, B & Tessier, S (2015); *Journal Rankings Effects on Junior Academics: Identity Fragmentation and Politicization*; Critical Perspectives on Accounting **26**: 84-98

Mansfield, E (1966); *The Economics of Science Policy;* The American Economic Review **56**(2):476-518

Mansfield, E (1991); *Academic Research and Industrial Innovation*; Research Policy **20**(1): 1-12

Mansfield, E (1998); *Academic Research and Industrial Innovation: An Update of Empirical Findings*; Research Policy **26**(7-8): 773-776

Manville, C, Guthrie, S, Henham, M-L, Garrod, B, Sousa, S, Kirtley, A, Castle-Clarke, S & Ling, T (2015); Assessing Impact Submissions for REF 2014: An Evaluation; Rand Europe; available from http://www.hefce.ac.uk/media/HEFCE,2014/Content/Pubs/Independentresearch/2015/REF,impact,submissions/REF_assessing_impact_submissions.pdf

Marabelli, M & Newell, S (2014); *Knowing, Power and Materiality: A Critical Review and Reconceptualization of Absorptive Capacity*; International Journal of Management Reviews **16**(4): 479-499

March, J (1991); *Exploration and Exploitation in Organizational Learning*; Organization Science **2**(1): 71-87

Martin-Rojas, R, Garcia-Morales, VJ & Bolivar-Ramos, MT (2013); *Influence of Technological Support, Skills and Competencies, and Learning on Corporate Entrepreneurship in European Technology Firms*; Technovation **33**(12): 417-430

Martinez-Conde, S (2016); *Has Contemporary Academia Outgrown the Carl Sagan Effect?*; The Journal of Neuroscience **36**(7):2077-2082

Martinez-Senra, AI, Quintas, MA, Sartal, & Vazquez, XH (2015); *Can Firms Basic Research Turn into Product Innovation? The Role of Absorptive Capacity and Industry Appropriability*; IEEE Transactions on Engineering Management **62**(2): 205 - 216

Marx, W (2011); *Special Features of Historical Papers from the Viewpoint of Bibliometrics*; Journal of the American Society for Information Science & Technology **62**(3): 433-439

Marx, W (2014); *The Shockley-Queisser Paper – A Notable Example of a Scientific Sleeping Beauty*; Annalen der Physik **526**(5-6):A41-A45

Marx, W, Bornmann, L, Barth, A & Leydesdorff, L (2014); *Detecting the Historical Roots of Research Fields by Reference Publication Year Spectroscopy (RPYS)*; Journal of the Association for Information Science & Technology **65**(4): 751-764

Massachusetts Institute of Technology (2015); 2015 MIT Facts; http://web.mit.edu/facts/alum.html accessed 3rd July 2015

Matthews, D (2015); *Is Industry Funding Undermining Trust in Science?*; Times Higher Education; https://www.timeshighereducation.com/features/is-industry-funding-undermining-trust-in-science

Mayne, J (2012); *Contribution Analysis: Coming of Age?*; Evaluation **18**(3):270-280

Mazzucato, M (2013); The Entrepreneurial State; Anthem Press; New York, USA; ISBN: 978 0 85728 252 1

McCain, KW (2014); *Obliteration by Incorporation*; In Cronin, B & Sugimoto, CR (eds); Beyond Bibliometrics Harnessing Multidimensional Indicators of Scholarly Impact; MIT Press, Cambridge USA; ISBN: 978-0-262-02679-6/978-0-262-52551-0; pp 129 - 149

McCann, BM, Cramer, CB & Taylor, LG (2015); *Assessing the Impact of Education and Outreach Activities on Research Scientists*; Journal of Higher Education Outreach and Engagement **19**(1):65-78

McColl, G (2015); *Innovation and Science Agenda 'Disastrous' for Humanities and Creative Industries*; The Sydney Morning Herald; 13 December 2015; http://www.smh.com.au/federalpolitics/politicalnews/innovationandscience-agendadisastrousforhumanitiesandcreativeindustries20151212glkcjb.html

McMillan, GS (2009); *Gender Differences in Patenting Activity: An Examination of the US Biotechnology Industry*; Scientometrics **80**(3): 683-691

McNeill, D (2014); *In Japan, Research Scandal Prompts Questions*; The Chronicle of Higher Education **60**(40):1543462817

Medical Research Council (2016); Guidance for Applicants 2016 v16.4; available from http://www.mrc.ac.uk/documents/pdf/guidance-for-applicants-v16-4/

Meho, LI & Rogers, Y (2008); *Citation Counting, Citation Ranking, and h-Index of Human-Computer Interaction Researchers: A Comparison of Scopus and Web of Science*; Journal of the American Society for Information Science and Technology **59**(11): 1711-1726

Melero, R (2015); *Altmetrics – A Complement to Conventional Metrics*; Biochemia Medica **25**(2):152-160

Mengersen, K, Moynihan, SA & Tweedie, RL (2007); *Causality and Association: The Statistical and Legal Approaches*; Statistical Science **22**(2):227-254

Merton, RK (1988); *The Matthew Effect in Science II Cumulative Advantage and the Symbolism of Intellectual Property*; Isis **79**(4):606-623

Messeni Petruzzelli, A, Rotolo, D & Albino, V (2015); *Determinants of Patent Citations in Biotechnology: An Analysis of Patent Influence Across the Industrial and Organizational Boundaries*; Technological Forecasting & Social Change **91**:208-221

Meyer, B, Choppy, C, Staunstrup, J & van Leeuwen, J (2009); *Research Evaluation for Computer Science*; Communications of the ACM **52**(4): 31- 34

Miedzinksi, M (Ed), (2013); Assessing Environmental Impacts of Research and Innovation Policy; Study for the European Commission, Directorate-General for Research and Innovation; Brussels; available from https://ec.europa.eu/research/evaluations/pdf/archive/other_reports_studies_and_documents/envti0413167enn_002.pdf

Michels, C & Schmoch, U (2014); *Impact of Bibliometric Studies on the Publication Behaviour of Authors*; Scientometrics **98**(1): 369-385

Milat, AJ, Bauman, AE & Redman, S (2015); *A Narrative Review of Research Impact Assessment Models and Methods*; Health Research Policy and Systems **13**(1): 18

Miller, K, McAdam, R, Moffett, S, Alexander, A & Puthusserry, P (2016); *Knowledge Transfer in University Quadruple Helix Ecosystems: An Absorptive Capacity Perspective*; R&D Management **46**(2): 383-399

Mindruta, D (2013); *Value Creation in University-Firm Research Collaborations: A Matching Approach*; Strategic Management Journal **34**(6):644-665

Minguillo, D, Tijssen, R & Thelwall, M (2015); *Do Science Parks Promote Research and Technology? A Scientometric Analysis of the UK*; Scientometrics **102**(1):701-725

Mirnezami, SR, Beaudry, C & Larivière, V (2016); *What Determines Researchers' Scientific Impact? A Case Study of Quebec Researchers*; Science and Public Policy **43**(2):262-274

(MIT) Massachusetts Institute of Technology (2011); The Third Revolution: The Convergence of the Sciences, Physical Sciences and Engineering; available from http://dc.mit.edu/sites/dc.mit.edu/files/MIT%20White%20Paper%20on%20Convergence.pdf

Moed, HF (2005); Citation Analysis in Research Evaluation; Springer; Dordrecht, The Netherlands; ISBN 1-4020-3713-9

Moed, HF (2005a); *Statistical Relationships Between Downloads and Citations at the Level of Individual Documents within a Single Journal*; Journal of the American Society for Information Science and Technology **56**(10):1088-1097

Moed, HF (2016); *Comprehensive Indicator Comparisons Intelligible to Non-Experts: The Case of Two SNIP Versions*; Scientometrics **106**(1):51-65

Moed, HF & Halevi, G (2016); *On Full Text Download and Citation Distribution in Scientific-Scholarly Journals*; Journal of the Association for Information Science and Technology **67**(2):412-431

Moed, HF, van Leeuwen, TN & Reedijk, J (1998); *A New Classification System to Describe the Ageing of Scientific Journals and Their Impact Factors*; Journal of Documentation **54**(4):387-419

Moed, HF & Visser, MS (2007); Developing Bibliometric Indicators of Research Performance in Computer Science: An Exploratory Study; Research Report to the Council for Physical Sciences of the Netherlands Organisation for Scientific Research, Centre for Science & Technology Studies (CWTS), University of Leiden; CWTS report 2007-01; available from http://www.cwts.nl/pdf/nwo_inf_final_report_v_210207.pdf

Mohammadi, E, Thelwall, M, Haustein, S & Larivière, V (2015); *Who Reads Research Articles? An Altmetric Analysis of Mendeley User Categories*; Journal of the Association for Information Science & Technology **66**(9):1832-1846

Mokyr, J (2011); The Enlightened Economy; Penguin; London, UK; ISBN: 978-0-14-196910-7

Mongeon, P & Paul-Hus, A (2016); *The Journal Coverage of* Web of Science *and* Scopus*: A Comparative Analysis*; Scientometrics **106**(1):213-228

Mooney, C (2009); *University Strives to be a Cultural Hub in Central Arkansas*; The Chronicle of Higher Education **55**(24):32722; available from http://chronicle.com/article/University-Strives-to-Be-a/32722

Moore, JF (1993); *Predators and Prey: A New Ecology of Competition*; Harvard Business Review **71**:75-86

Moretti, E (2010); *Local Multipliers*; American Economic Review **100**(2): 373 – 377

Morgan Jones, M, Castle-Clarke, S, Manville, C, Gunashekar, S & Grant, J (2013); Assessing Research Impact An International Review of the Excellence in Innovation for Australia Trial; RAND Europe for the Australian Technology Network of Universities; available from https://www.atn.edu.au/Documents/Publications/RR-278-ATN%20Assessing%20Research%20Impact%20v1%200.pdf

Morris, N & Rip, A (2006); *Scientists' Coping Strategies in an Evolving Research System: The Case of Life Scientists in the UK*; Science and Public Policy **33**(4):253-263

Morton, S (2012); Exploring and Assessing Social Research Impact: A Case Study of a Research Partnership's Impacts on Policy and Practice; PhD Thesis; The University of Edinburgh.

Morton, S (2015); *Progressing Research Impact Assessment: A 'Contributions' Approach*; Research Evaluation **24**(4):405-419

Motohashi, K (2013); *The Role of the Science Park in Innovation Performance of Start-up Firms: An Empirical Analysis of Tsinghua Science Park in Beijing*; Asia Pacific Business Review **19**(4): 578-599

Moy, JW & Lee, SM (2002); *The Career Choice of Business Graduates: SMEs or MNCs?*; Career Development International **7**(6): 339-347

Moyo, S & Williamson, C (2016); *Measuring Research Performance and Research Impact: A South African Case Study*; International Network of Research Management Societies 2016 Congress (INORMS 2016); 11 – 15 September 2016; Melbourne, Australia

Nabout, JC, Parreira, MR, Teresa, FB, Carneiro, FM, Ferreira da Cunha, H, de Souza Ondei, L, Caramori, SS & Soares, TN (2015); *Publish (in a Group) or Perish (Alone): The Trend from Single- to Multi- Authorship in Biological Papers*; Scientometrics **102**(1):357-364

National ICT Australia Ltd (2014); NICTA Report 2013; available from http://www.nicta.com.au/content/uploads/2015/02/NICTA_Report_2013_4MB.pdf

National Research Council (1996); World-Class Research and Development: Characteristics for an Army Research, Development, and Engineering Organization; Standing Committee on Program and Technical Review of the US Army Natick Research, Development and Engineering Centre, Board on Army Science and Technology, Commission on Engineering and Technical Systems; The National Academies Press; Washington DC, USA; ISBN: 0-309-56201-5

National Research Council (1997); Assessment of the US Army Natick Research, Development and Engineering Centre; Standing Committee on Program and Technical Review of the US Army Natick Research, Development and Engineering Centre, Board on Army Science and Technology, Commission on Engineering and Technical Systems; The National Academies Press; Washington DC, USA; ISBN: 0-309-59686-6

National Research Council (2009); A New Biology for the 21st Century; Committee on a New Biology for the 21st Century: Ensuring the United States Leads the Coming Biology Revolution, Board on Life Sciences; National Academies Press; Washington DC, USA; ISBN: 0-309-14486-8

National Research Council (2010); Persistent Forecasting of Disruptive Technologies; Committee on Forecasting Future Disruptive Technologies; The National Academies Press; Washington DC, USA; ISBN: 0-0309-11660-0

National Research Council (2012); Best Practices in Assessment of Research and Development Organizations; Panel for Review of Best Practices in Assessment of Research and Development Organizations, Laboratory Assessments Board, Division on Engineering and Physical Sciences; The National Academies Press; Washington DC, USA; ISBN: 978-0-309-26626-0

National Research Council (2014); Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences and Beyond; The National Academies Press; Washington DC, USA; ISBN: 978-0-309-30151-0

National Science Foundation (2009); Proposal and Award Policies and Procedures Guide Part 1 – Proposal Preparation & Submission Guidelines GPG; available at www.nsf.gov/pubs/policydocs/pappguide/nsf10_1/gpgprint.pdf

National Science Foundation (2012) http://www.nsf.gov (accessed 3rd March 2012)

National Science Foundation (2013); National Centre for Science & Engineering Statistics, Science & Engineering Statistical Data System (SESTAT Data Tool) - Survey of Doctoral Recipients SDR Public 2013; available from https://www.nsf.gov/statistics/srvydoctoratework/

National Science Foundation (2013); Proposal and Award Policies and Procedures Guide Part 1 – Grant Proposal Guide; Document Number: gpg13001; available at www.nsf.gov/publications/pub_summ.jsp?ods_key=gpg

Natural Sciences and Engineering Research Council of Canada (2012); http://www.nserc-crsng.gc.ca/NSERC-CRSNG/Committees-Comites/programs-programmes_eng.asp (accessed 3rd March 2012)

Nature Chemical Biology Editors (2010); *On Citing Well*; Nature Chemical Biology **6**(2):79

Neicu, D, Teirlick, P & Kelchtermans, S (2016); *Dipping in the Policy Mix: Do R&D Subsidies Foster Behavioral Additionality Effects of R&D Tax Credits?*; Economics of Innovation and New Technology **25**(3):218-239

Nelson, RR & Phelps, ES (1966); *Investment in Humans, Technological Diffusion and Economic Growth*; American Economic Review **56**(2): 69 – 75

Neuhäusler, P & Frietsch, R (2012); *Patent families as Macro Level Patent Value indicators: Applying Weights to Account for Market Differences*; Scientometrics **96**(1): 1-23

Neuhäusler, P, Frietsch, R, Schubert, T & Blind, K (2011); Patents and the Financial Performance of Firms – An Analysis Based on Stock Market Data; Fraunhofer ISI Discussion Papers Innovation Systems and Policy Analysis No. 28; available from http://www.isi.fraunhofer.de/isi-wAssets/docs/p/de/diskpap_innosysteme_policyanalyse/discussionpaper_28_2011.pdf

Newson, R, King, L, Rychetnik, L, Bauman, AE, Redman, S, Milat, AJ, Schroeder, J, Cohen, G & Chapman, S (2015); *A Mixed Methods Study of the Factors that Influence Whether the Intervention Research has Policy and Practice Impacts: Perceptions of Australian Researchers*; BMJ Open **5**(7): e008153

(NHMRC) National Health & Medical Research Council (2013); 2012 NHMRC Project Grants Application Round – Statistical Analysis; available from https://www.nhmrc.gov.au/grants-funding/outcomes-funding-rounds/previous-outcomes-project-grants-funding-rounds

Nieder, C, Dalhaug, A & Aandahl, G (2013); *Correlation Between Article Download and Citation Figures for Highly Accessed Articles from Five Open Access Oncology Journals*; SpringerPlus **2**:261

Nieto, M & Quevedo, P (2005); *Absorptive Capacity, Technological Opportunity, Knowledge Spillovers, and Innovative Effort;* Technovation **25**(10): 1141-1157

Noel, M & Schankerman, M (2013); *Strategic Patenting and Software Innovation*; The Journal of Industrial Economics **61**(3): 481-520

OECD (2007) Information Economy – Sector Definitions Based on the International Standard Industry Classification (ISIC 4); OECD Publishing; Paris, France;

OECD (2011); OECD Science, Technology and Industry Scoreboard 2011; OECD Publishing; Paris, France; ISBN: 9789264111653

OECD (2014); Main Science and Technology Indicators; Vol 2014/1; OECD Publishing; Paris, France;

OECD (2015); Research and Development Statistics – Expenditure – Gross Domestic Expenditure on R&D by Sector of Performance and Source of Funds; http://stats.oecd.org/

OECD (2015a); Research and Development Statistics – Personnel – R&D Personnel by Sector of Employment and Occupation; http://stats.oecd.org/

OECD (2015b); Government at a Glance 2015; OECD Publishing; Paris, France; ISBN: 978-92-64-23347-8

OECD (2016); Science, Technology and R&D Statistics – Main Science & Technology Indicators; http://www.oecd-ilibrary.org/science-and-technology/data/oecd-science-technology-and-r-d-statistics/main-science-and-technology-indicators_data-00182-en?isPartOf=/content/datacollection/strd-data-en

Office of the Chief Scientist (2014); Benchmarking Australian Science, Technology, Engineering and Mathematics; Australian Government, Canberra; ISBN: 978 1 925095 45 5

Okamuro, H & Nishimura, J (2013); *Impact of University Intellectual Property Policy on the Performance of University-Industry Research Collaboration*; Journal of Technology Transfer **38**(3): 273-301

Okuda, Y & Tanaka, Y (2011); *How are Defensive Patents Defined and Utilized as Business Strategic Tools? Questionnaire Survey to Japanese Enterprises Having Many Defensive Patents*; Portland International Conference on Management of Engineering and Technology (PICMET '11); Portland, USA; 31 July – 4 August 2011; pp: 1-8

Oksanen, K & Hautamaki, A (2014); *Transforming Regions into Innovation Ecosystems: A Model for Renewing Local Industrial Structure*s; The Innovation Journal: The Public Sector Innovation Journal **19**(2): 5

O'Leary, DE (2008); *The Relationship Between Citations and Number of Downloads in Decision Support Systems*; Decision Support Systems **54**(4):972-980

Oliver, K, Innvar, S, Lorenc, T, Woodman, J & Thomas, J (2014); *A Systematic Review of Barriers to and Facilitators of the Use of Evidence by Policymakers*; BMC Health Services Research **14**:2

Olsen, S & Merrill, S (2011) Measuring the Impacts of Federal Investments in Research: A Workshop Summary; The National Academies Press; Washington USA; ISBN: 13:978-0-309-21748-4 /10:0-309-21748-2

Ooms, W, Werker, C, Canieëls, MCJ & van den Bosch, H (2015); *Research Orientation and Agglomeration: Can Every Region Become a Silicon Valley?*; Technovation **45-46**:78-92

O'Reilly, CA & Tushman, ML (2007); Ambidexterity as a Dynamic Capability: Resolving the Innovator's Dilemma; Stanford Graduate School of Business Research Paper No. 1963; available from https://www.gsb.stanford.edu/gsb-cmis/gsb-cmis-download-auth/318756

O'Reilly, CA & Tushman, ML (2013); *Organizational Ambidexterity: Past, Present, and Future*; The Academy of Management Perspectives **27**(4): 324-338

Ouimet, M, Bedard, P-O, Leon, G & Dagenais, C (2014); *Are Indicators of Faculty Members' Credibility Associated with How Often They Present Research Evidence to Public or Partly Government-Owned Organisations? A Cross-Sectional Survey*; Evidence & Policy **10**(1): 5 - 27

Oxford Dictionary of English (2005) 2nd Edition Revised; Oxford University Press; Oxford, UK;

Oxford Economics (2013); The Impact of the University of Birmingham; available from http://www.birmingham.ac.uk/Documents/university/economic-impact-of-university-of-birmingham-full-report.pdf

Oxford Martin School (2015); Wealth Creation, Not Job Creation is Impact of Tech Industries: Oxford Martin School Study Shows that Less than 0.5% of US Jobs Have Been Created by Technology Industries So Far This Century; http://www.oxfordmartin.ox.ac.uk/news/151202_tech_employment accessed 5 February 2016

Özçelik, E & Tayman, E (2008); *R&D Support Programs in Developing Countries: The Turkish Experience*; Research Policy **37**(2):258-275

Pajić, D (2015); *On the Stability of Citation-Based Journal Rankings*; Journal of Informetrics **9**(4):990-1006

Pan, X, Yan, E, Wang, Q & Hua, W (2015); *Assessing the Impact of Software on Science: A Bootstrapped Learning of Software Entities in Full-Text Papers*; Journal of Informetrics **9**(4): 860-871

Park, W (1995); *International R&D Spillovers and OECD Economic Growth*; Economic Enquiry **33**(4): 571-591

Parliament of Australia (2011); Budget Review 2011-12; available from http://www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/pubs/rp/BudgetReview201112

Parliament of Victoria (2010); Inquiry into Manufacturing in Victoria Report of the Economic Development and Infrastructure Committee on the Inquiry into Manufacturing in Victoria; Parliamentary Paper No.331 Session 2006-10; Victorian Government Printer, Melbourne; ISBN 978 0 9751357 9 5

Parta, D & David, PA (1994); *Towards a New Economics of Science*; Research Policy **23**(5):487-521

Paruolo, P, Saisana, M & Saltelli, A (2013); *Ratings and Rankings: Voodoo or Science?* Journal of the Royal Statistical Society Series A: Statistics in Society **176**(3): 609-634

Paul-Hus, A, Desrochers, N & Costas, R (2016); *Characterization, Descriptions and Considerations for the Use of Funding Acknowledgement Data in Web of Science*; Scientometrics **108**(1):167-182

Pearce, J (2015); *Quantifying the Value of Open Source Hardware Development*; Modern Economy **6**(1):1-11

Pearl, J (2009); *Causal Inference in Statistics: An Overview*; Statistics Surveys **3**:96-146

Pencheon, DC (2011); *Managing the Environmental Impact of Research*; Trials **12**(1):80-81

Penfield, T, Baker, MJ, Scoble, R & Wykes, MC (2014); *Assessment, Evaluations, and Definitions of Research Impact: A Review*; Research Evaluation **23**(1): 21–32

Perez-Astray, B & Calvio Babio, N (2011); *Analysis of the Interface Systems as Mediating Agents in University/Industry Relations. Proposal of the "Relationship Promoter" as a Strategic Role in the R&D Transference*; European Research Studies **XIV**(1): 57-70

Peritz, BC (1995); *On the Association Between Journal Circulation and Impact Factor*; Journal of Information Science **21**(1):63-67

Perkmann, M, Fini, R, Ross, J-M, Salter, A, Silvestri, C & Tartari, V (2015); *Accounting for Universities' Impact: Using Augmented Data to Measure Academic Engagement and Commercialization by Academic Scientists*; Research Evaluation **24**(4):380-391 1

Perkmann, M, King, Z & Pavelin, S (2011); *Engaging Excellence? Effects of Faculty Quality on University Engagement with Industry;* Research Policy **40**(4):539-552

Peters, I, Kraker, P, Lex, E, Gumpenberger, C & Gorraiz, J (2015); *Research Data Explored: Citation versus Altmetrics*; 15th International Conference on Scientometrics & Informetrics (ISSI 2015); Ref: 0172; 29 June – 4 July 2015; Istanbul, Turkey

Peters, I, Kraker, P, Lex, E, Gumpenberger, C & Gorraiz, J (2016); *Research Data Explored: An Extended Analysis of Citations and Altmetrics*; Scientometrics **107**(2):723-744

Pew Research Centre (2014); Online Harassment; available from http://www.pewinternet.org/2014/10/22/online-harassment/

Pew Research Centre (2015); Public and Scientist's Views on Science and Society; Available from http://www.pewinternet.org/files/2015/01/PI_ScienceandSociety_Report_012915.pdf

Philbin, SP (2010); *Developing and Managing University-Industry Research Collaborations Through a Process Methodology / Industrial Sector Approach*; Journal of Research Administration **41**(3): 51-68

Piketty, T (2014); Capital in the Twenty-First Century; Translated by A Goldhammer; Belknap Press of Harvard University Press; Cambridge, USA; ISBN: 978-0-674-43000-6

Piro, FN & Sivertsen, G (2016); *How Can Difference in International University Rankings be Explained?*; Scientometrics **First Online** DOI 10.1007/s11192-016-2056-5

Polanyi, M (1958); Personal Knowledge Towards a Post-Critical Philosophy; Routledge; London, UK; 2005 Edition; ISBN: 0-203-44215-6

Pollitt, A, Potoglou, D, Patil, S, Burge, P, Guthrie, S, King, S, Wooding, S & Grant, J (2016); *Understanding the Relative Valuation of Research Impact: A Best-Worst Scaling Experiment of the General Public and Biomedical and Health Researchers*; BMJ Open **6**(8):e010916

Ponomariov, BL & Boardman, C (2010); *Influencing Scientists Collaboration and Productivity Patterns Through New Institutions: University Research Centres and Scientific and Technical Human Capital;* Research Policy **39**(5):613-624

Pontis, S & Blandford, A (2016); *Understanding "Influence": An Empirical Test of the Data-Frame Theory of Sensemaking;* Journal of the Association for Information Science and Technology **67**(4):841-858

Popp Berman, E (2012); Creating the Market University: How Academic Science Became an Economic Engine; Princeton University Press; Princeton, USA; ISBN: 978-0-691-14708-6

Prathap, G, Mini, S & Nishy, P (2016); *Does Impact Factor Successfully Predict Future Citations? An Analysis using Peirce's Measure*; Scientometrics **108**(3):1043-1047

Prettner, K & Werner, K (2016); *Why it Pays Off to Pay Us Well: The Impact of Basic Research on Economic Growth and Welfare*; Research Policy **45**(5):1075-1090

Price, AM & Peterson, LP (2016); *Scientific Progress, Risk, and Development: Explaining Attitudes Toward Science Cross-Nationally*; International Sociology **31**(1):57-80

Priem, J, Taraborelli, D, Groth, P & Neylon, C (2010); Altmetrics: A Manifesto; http://altmetrics.org/manifesto

Productivity Commission (2007); Public Support for Science and Innovation; Research Report; Productivity Commission, Canberra, Australia; ISBN: 9781-1-74037-225-1; Available from http://apo.org.au/files/Resource/science.pdf

Productivity Commission (2003); Trends in Australian Manufacturing; Commission Research Paper; AusInfo; Canberra; available from http://www.pc.gov.au/research/completed/manufacturing/tiam.pdf

(PwC) PriceWaterhouseCoopers (2014); R&D Outsourcing in Hi-Tech Industries A Research Study; available from http://www.pwc.com/gx/en/industries/pharmaceuticals-life-sciences/publications/high-tech-research-development-outsourcing.html

(PwC) PriceWaterhouseCoopers (2015); Innovate and Prosper Ensuring Australia's Future Competitiveness Through University-Industry Collaboration; Report prepared for the Australian Technology Network of Universities and the AI Group; available from https://www.atn.edu.au/Documents/Publications/Reports/2015/ATN%20Innovate%20and%20Prosper_web_version.pdf

Qiu, J (2010); *Publish or Perish in China*; Nature **463**(7278):142-143

Radicchi, F & Castellano, C (2011); *Rescaling Citations of Publications in Physics*; Physical Review E **83**(4):046116

Rafols, I, Leydesdorff, L. O'Hare, A, Nightingale, P & Stirling, A (2012); *How Journal Rankings Can Suppress Interdisciplinary Research: A Comparison Between Innovation Studies and Business & Management*; Research Policy **41**(7):1262-1282

Rahm, E (2008); *Comparing the Scientific Impact of Conference and Journal Publications in Computer Science*; Information Services & Use **28**(2): 127-128

Rantisi, NM & Leslie, D (2015); *Significance of Higher Educational Institutions as Cultural Intermediaries: The Case of the École nationale de cirque in Montreal, Canada*; Regional Studies **49**(3):404-417

Regional Universities Network (2013); Regional Universities Network: Engaging with Regions, Building a Stronger Nation; Vol 1; available from http://www.run.edu.au/resources/RUN_regional_impact_study_vol_1.pdf

Reid, G (2014); Why Should the Taxpayer Fund Science and Research; National Centre for Universities and Business; available from http://www.ncub.co.uk/reports/why-science.html

Research Council of Norway (2015); *Societal Impact of Research to be Evaluated*; http://www.forskningsradet.no/en/Newsarticle/Societal_impact_of_research_to_be_evaluated/1254014134659/p1177315753918 (accessed 20 January 2016)

Research Excellence Framework (2013); All FAQs About the Research Excellence Framework (REF); http://www.ref.ac.uk/about/guidance/faq/all/; accessed 21 March 2016

Resnick, HE, Sawyer, K & Huddlestone, N (2015); Trust and Confidence at the Interfaces of the Life Sciences and Society. Does the Public Trust Science? A Workshop Summary; National Academies Press; Washington, USA; ISBN: 978-0-309-37792-8

Rigby, J (2011); *Systematic Grant and Funding Body Acknowledgement Data for Publications: New Dimensions and New Controversies for Research Policy and Evaluation*; Research Evaluation **20**(5): 365 – 375

Rigby, J (2013); *Looking for the Impact of Peer Review: Does Count of Funding Acknowledgements Really Predict Research Impact?* Scientometrics **94**(1): 57 – 73

Ringelhan, S, Wollersheim, J & Welpe, IM (2015); *I Like, I Cite? Do Facebook Likes Predict the Impact of Scientific Work?;* PloS ONE **10**(8):e0134389

Roberts, EB, Murray, F & Kim JD (2015); Entrepreneurship and Innovation at MIT Continuing Global Growth and Impact; Martin Trust Centre for MIT Entrepreneurship; Massachusetts, USA; available from http://entrepreneurship.mit.edu/sites/default/files/documents/EntrepreneurshipInnovationMIT-8Dec2015-final.pdf

Roberts, N (2015); *Absorptive Capacity, Organizational Antecedents, and Environmental Dynamism*; Journal of Business Research **68**(11): 2426-2433

Roessner, JD, et al (2008); National and Regional Economic Impacts of Engineering Research Centres: A Pilot Study Final Report; SRI International; November 2008

Rog, DJ (2012); *When Background Becomes Foreground: Toward Context Sensitive Evaluation Practice*; in Rog, DJ, Fitzpatrick, JL & Conner RF, (Eds), Context: A Framework for its Influence on Evaluation Practice; New Directions for Evaluation **135**:25-40

Roorda, S (2009); *The Real Cost of the NSERC Peer Review is Less Than 5% of a Proposed Baseline Grant*; Accountability in Research **16**(4): 229-231

Rosemberg, C, Simmonds, P, Potau, X, Farla, K, Sharp, T, Wain, M, Cassagneau-Francis, O & Kovacs, H (2015); Assessing the Economic Returns of Engineering Research and Postgraduate Training in the UK; Report prepared by the Technopolis Group for the Royal Academy of Engineering; available from http://www.raeng.org.uk/publications/reports/assessing-the-economic-returns-of-engineering-rese

Rosenberg, N (1990); *Why Do Firms Do Basic Research (With Their Own Money)?*; Research Policy **19**(2):165-174

Ross, C (2015); *Convergence of Computing, Biogenetics and Cognitive Neuroscience*; IT NOW **57**(3):48-51

Rural Research and Development Council (2011); National Strategic Rural Research and Development Investment Plan; Government of Australia; ISBN: 978-1-921575-27-3

Russell, TG & Sugimoto, CR (2009); *MPACT Family Trees: Quantifying Academic Genealogy in Library and Information Science*; Journal of Education for Library and Information Science **50**(4): 248 – 262

Ryan, M (2012); *The Production of Scientific Output by Early-Career Researchers*; XXI Conference of the Association for Economic Education; Porto, Portugal; 5-6 July 2012

Salimi, N, Bekkers, R & Frenken, K (2015); *Does Working with Industry Come at a Price? A Study of Doctoral Candidates' Performance in Collaborative vs Non-Collaborative PhD Projects*; Technovation **41-42**:51-56

Samuel, GN & Derrick, GE (2015); *Societal Impact Evaluation: Exploring Evaluator Perceptions of the Characterization of Impact Under the REF2014*; Research Evaluation **24** (3): 229-241

Sandu, S & Ciocanel, B (2014); *Impact of R&D and Innovation on High-Tech Export*; Procedia Economics and Finance **15**: 80-90

Sandberg, AB, Pareto, L & Arts, T (2011); *Agile Collaborative Research: Action Principles for Industry-Academia Collaboration*; IEEE Software **28**(4): 74 – 83

Schlögl, C, Gorraiz, J, Gumpenberger, C, Jack, K & Kraker, P (2014); *A Comparison of Citations, Downloads and Readership Data for an Information Systems Journal*; Research Trends Issue 37 (June 2014); available from http://www.researchtrends.com/issue-37-june-2014/a-comparison-of-citations-downloads-and-readership-data/

Schneider, JW, Aagaard, K & Bloch, CW (2016); *What Happens When National Research Funding is Linked to Differentiated Publication Counts? A Comparison of the Australian and Norwegian Publication-Based Funding Models*; Research Evaluation **25**(3):244-256

Schneider, SL, Ness, KK, Rockwell, S, Shaver, K & Brutkiewicz, R (2014); 2012 Faculty Workload Survey Research Report; Federal Demonstration Partnership; available from http://sites.nationalacademies.org/cs/groups/pgasite/documents/webpage/pga_087667.pdf

Schofield, T (2013); *Critical Success Factors for Knowledge Transfer Collaborations between University and Industry*; Journal of Research Administration **44**(2):38-56

Schwab, K, Sala-i-Martin, X, Barth Eide, E & Blanke, J (2014); The Global Competitiveness Report 2014 – 2015; World Economic Forum, Switzerland; ISBN: 978-92-95044-98-2

Seglen, PO (1994); *Causal Relationship between Article Citedness and Journal Impact*; Journal of the American Society for Information Science **45**(1):1-11

Seneca, JJ, Lahr, ML & Irving, W (2014); Contribution of the Life Sciences Industry to the New Jersey Economy; Report prepared for BioNJ by the Edward J Bloustein School of Planning and Public Policy, Rutgers University; New Brunswick, USA; available from http://bloustein.rutgers.edu/wp-content/uploads/2015/03/Economic-Contributions-of-Life-Sciences-EJBPPP.pdf

Scottish Science Advisory Council (2009); Business R&D in Scotland – A Missing Link; ISBN: 978-0-7559-5922-8

Shahiduzzaman, M, Layton, A & Alam, K (2015); *On the Contribution of Information and Communication Technology to Productivity Growth in Australia*; Economic Change and Restructuring **48**(3):281-304

Shanks, S & Zheng, S (2006); Econometric Modelling of R&D and Australia's Productivity; Productivity Commission Staff Working Paper; Commonwealth of Australia; Canberra Australia; ISBN: 1 74037 200 X

Shao, J & Shen, H (2011); *The Outflow of Academic Papers from China: Why is it Happening and Can it be Stemmed?*; Learned Publishing **24**(2): 95-97

Shapira, P, Youtie, J & Kay, L (2011); *National Innovation Systems and the Globalization of Nanotechnology Innovation*; Journal of Technology Transfer **36**(6): 587-604

Shapiro, C (2001); *Navigating the Patent Thicket: Cross Licenses, Patent Pools and Standard Setting*; NBER Innovation Policy & the Economy **1**(1):119-150

Sharp, PA (2014); *Meeting Global Challenges: Discovery and Innovation through Convergence*; Science **346**(6216):1468-1471

Sharp, PA & Langer, R (2011); *Promoting Convergence in Biomedical Science*; Science **333**(6042):527

Shea, C (2011); *As Dutch Research Scandal Unfolds, Social Psychologists Question Themselves; Even Legitimate Researchers Cut Corners, Some Admit*; The Chronicle of Higher Education **58**(13): 904276320

Shema, H, Bar-Ilan, J & Thelwall, M (2014); *Do Blog Citations Correlate with a Higher Number of Future Citations? Research Blogs as a Potential Source for Alternative Metrics*; Journal of the Association for Information Science & Technology **65**(5):1018-1027

Shepherd, R (2014); *Culture Shift Required: Improving the Economic Impact of Australian Research*; AQ – Australian Quarterly **85**(1): 14-20

Shrivastava, R (2015); *Relationship Between ResearchGate Altmetric Indicators and Scopus Bibliometric Indicators: The Case of Panjab University Chandigarh (India)*; New Library World **116**(9/10):564-577

Shrivastava, R & Mahajan, P (2016): *Relationship between Citation Counts and Mendeley Readership Metrics*; New Library World **117**(3/4):229-238

Shuai, X, Pepe, A & Bollen, J (2012); *How the Scientific Community Reacts to Newly Submitted Preprints: Article Downloads, Twitter Mentions and Citations*; PloS One **7**(11):e47523

Shu, C, Wang, Q, Gao, S & Liu, C (2015); *Firm Patenting, Innovations, and Government Institutional Support as a Double-Edged Sword*; Journal of Product Innovation Management **32**(2): 290-305

Siegel, DS, Westhead, P & Wright, M (2003); *Science Parks and the Performance of New-Technology Based Firms: a Review of Recent UK Evidence and an Agenda for Future Research*; Small Business Economics **20**(2): 177-184

Sigurdson, K, Sa, CM & Kretz, A (2015); *Looking Under the Street Light: Limitations of Mainstream Technology Transfer Indicators*; Science and Public Policy **42**(5):632-645

Simons, H (2015); *Interpret in Context: Generalizing from the Single Case in Evaluation*; Evaluation **21**(2):173-188

Smith, R (2006); *Peer Review: A Flawed Process at the Heart of Science and Journals*; Journal of the Royal Society of Medicine **99**(4): 178 – 182

Soh, P-H & Subramanian, AM (2014); *When Do Firms Benefit from University-Industry R&D Collaborations? The Implications of Firm R&D Focus on Scientific Research and Technological Recombination*; Journal of Business Venturing **29**(6):807-821

Sohn, DW & Kenney, M (2007); *Universities, Clusters, and Innovation Systems: The Case of Seoul, Korea*; World Development **35**(6): 991-1004

Spaapen, J & van Drooge, L (2011); *Introducing 'Productive Interactions' in Social Impact Assessment*; Research Evaluation **20**(3): 211 – 218

Spaapen, J, van Drooge, L, Propp, T, van der Meulen, B, Shinn, T, Marcovich, A, van den Besselaar, P, De Jong, S, Barker, K, Cox, D, Morrison, K, Sveinsdottir, T, Pearson, D, D'Ippolito, B, Prins, A, Molas-Gallart, J, Tang, P & Castro-Martinez, E (2011); SIAMPI Final Report; available from http://www.siampi.eu/Content/SIAMPI_Final%20report.pdf

Sparkes, M (2014); *The Nine Worst Predictions in the History of Technology*; The Guardian; 24 November 2014; available from http://www.telegraph.co.uk/technology/technology-topics/11196145/The-six-worst-predictions-in-the-history-of-technology.html

Spier, R (2002); *The History of the Peer-Review Process;* Trends in Biotechnology; **20**(8): 357 – 358

Spier, R (2002a); *Peer Review and Innovation*; Science and Engineering Ethics **8**(1):99-108

Spitz, A (2004); Are Skill Requirements in the Workplace Rising? Stylized Facts and Evidence on Skill-Biased Technological Change; Centre for European Economic Research Discussion Paper No. 04-33; available from ftp://ftp.zew.de/pub/zew-docs/dp/dp0433.pdf

Sterckx, S (2011); *Patenting and Licensing of University Research: Promoting Innovation or Undermining Academic Values?*; Science & Engineering Ethics **17**(1):45-64

Stevenson, B & Wolfers, J (2011); *Trust in Public Institutions Over the Business Cycle*; American Economic Review: Papers & Proceedings **101**(3):281-287

Stichweh, R (2015); *Scientific Disciplines, History of* ; in JD Wright (Ed) International Encyclopedia of the Social & Behaviour Sciences; 2nd Edition; Elsevier; Amsterdam, The Netherlands; ISBN: 978-0-08-097087-5; **vol 21**:287-290

Su, Z, Ahlstrom, D, Li, J & Cheng, D (2014); *Knowledge Creation Capability, Absorptive Capacity, and Product Innovativeness*; R&D Management **43**(5): 473-485

Suhrbier, A & Poland, GA (2013); *Are Impact Factors Corrupting Truth and Utility in Biomedical Research?* Vaccine **31**(51): 6041-6042

Sussex, J, Feng, Y, Mestre-Ferrandiz, J, Pistollato, M, Hafner, M Burridge, P & Grant, J (2016); *Quantifying the Economic Impact of Government and Charity Funding of Medical Research on Private Research and Development Funding in the United Kingdom*; BMC Medicine **14**:32

Szajnfarber, Z & Weigel, AL (2010); Innovation Pathways in Bureaucratic Organizations: A Process Study of Technology Infusion at NASA; Industry Studies Working Paper WP-2010-04; available from http://isapapers.pitt.edu/

Tahamtan, I, Safipour Afshar, A & Ahamdzadeh, K (2016); *Factors Affecting Number of Citations: A Comprehensive Review*; Scientometrics **107**(3);1195-1225

Tang, SHK (2015); *Does Research and Development Intensity Enhance Industrial Growth Performance During Economic Downturns? Inter-Industry Evidence from Australia*; The Australian Economic Review **48**(3):243-57

Tarnow, E (2002); *Coauthorship in Physics*; Science and Engineering Ethics **8**(1): 175-190

Tartari, V, Perkmann, M & Salter, A (2014); *In Good Company: The Influence of Peers on Industry Engagement by Academic Scientists*; Research Policy **43**(7):1189-1203

Tassey, G (2003); Planning Report 03-1 Method for Assessing the Economic Impacts of Government R&D; National Institute of Standards & Technology; USA; September 2003

Tassey, G (2010); *Rationales and Mechanisms for Revitalizing US Manufacturing R&D Strategies*; Journal of Technology Transfer **35**(3): 283-333

Taylor, M (2013); *The Challenge of Measuring Social Impact Using Altmetrics*; Research Trends Issue 33 (June 2013); available from http://www.researchtrends.com/issue-33-june-2013/the-challenges-of-measuring-social-impact-using-altmetrics/

Tee, KF (2016); *Suitability of Performance Indicators and Benchmarking Practices in UK Universities*; Benchmarking: An International Journal **23**(3):584-600

Teirlinck, P & Spithoven, A (2015); *How the Nature of Networks Determines the Outcome of Publicly Funded University Research Projects*; Research Evaluation **24**(2):158-170

Teixeira, AAC & Queiros, ASS (2016); *Economic Growth, Human Capital and Structural Change: A Dynamic Panel Data Analysis*; Research Policy **45**(8):1636-1648

Thelwall, M, Haustein, S, Larivière, V & Sugimoto, V (2013); *Do Altmetrics Work? Twitter and Ten Other Social Web Services*; PloS ONE **8**(5): e64841

Thelwall, M & Kousha, K (2015): *ResearchGate: Disseminating, Communicating and Measuring Scholarship?*; Journal of the Association for Information Science & Technology **66**(5):876-889

Thelwall, M & Kousha, K (2015a); *Web Indicators for Research Evaluation Part 2: Social Media Metrics*; El Profesional de la Información **24**(5):607-620

Thelwall, M, Kousha, K, Dinsmore, A & Dolby, K (2016); *Alternative Metric Indicators for Funding Scheme Evaluations*; Aslib Journal of Information Management **68**(1):2-18

Thomson Reuters ISI Web of Knowledge Journal Citation Reports Science Edition 2012 (www.wokinfo.com/products_tools/analytical/jcr/) accessed 15th February 2014

Thursby, JG, Fuller, A & Thursby, MC (2009); *US Faculty Patenting: Inside and Outside the University*; Research Policy **38**(1):14-25

Thursby, JG & Thursby, MC (2011); *Faculty Participation in Licensing: Implications for Research*; Research Policy **40**:20-29

Todorova, G & Durisin, B (2007); *Absorptive Capacity: Valuing a Reconceptualization*; The Academy of Management Review **32**(3): 774-786

Toole, AA, Czarnitzki, D & Rammer, C (2015); *University Research Alliances, Absorptive Capacity, and the Contribution of Startups to Employment Growth*; Economics of Innovation and New Technology **24**(5):532-549

Torrisi, S, Gambardella, A, Giuri, P, Hartoff, D, Hoisl, K & Mariani, M (2016); *Used, Blocked and Sleeping Patents: Empirical Evidence from a Large-Scale Inventor Survey*; Research Policy **45**(7):1374-1385

Trueger, NS, Thoma, B, Hsu, CC, Sullivan, D, Peters, L & Lin, M (2015); *The Altmetric Score: A New Measure for Article-Level Dissemination and Impact*; Annals of Emergency Medicine **66**(5):549-553

Tsai, C-F (2014); *Citation Impact Analysis of Top Ranked Computer Science Journals and Their Rankings*; Journal of Informetrics **8**(2):318-328

Tsai-Lin, T-F, Chang, Y-C & Katzy, BR (2014); *The Longitudinal Impact of Academic Patenting on Publishing Behaviour: Evidences from Taiwan (2001 – 2010)*; PICMET 2014 Portland International Centre for Management of Engineering and Technology, Proceedings: Infrastructure and Service Integration; Kanazawa, Japan; 27 – 31 July 2014; pp: 3263-3271

Turner, G (2016); *Four Myths: The Inconvenient Truth About Higher Education Funding*; The Australian; 24 February 2016;

UK Evaluation Forum (2006); Medical Research: Assessing the Benefits to Society; ISBN: I-903401-12-7;

United Nations (2015); Population and Vital Statistics Report; Statistical Papers Series A, Volume LXVII; ISBN: 978-92-1-161593-7

United Nations (2015a); Goal 3: Ensure Healthy Lives and Promote Well-being for All at All Ages; http://www.un.org/sustainabledevelopment/health/ ; accessed 30th December 2015

Schluep, M, Hagelueken, C, Kuehr, R, Magalini, F, Maurer, C, Meskers, C, Mueller, E & Wang, F (2009); Recycling – From E-Waste to Resources; Sustainable Innovation and Technology Transfer Industrial Sector Studies; United Nations Environment Program; available from http://www.unep.org/PDF/PressReleases/E-Waste_publication_screen_FINALVERSION-sml.pdf

United States Census Bureau (2102); Statistics of US Businesses (SUSB) Data Tables by Enterprise Employment Size; http://www.census.gov/econ/susb/

United States Census Bureau (2013); American Community Survey http://www.census.gov/programs-surveys/acs/data/pums.html

United States Department of Health & Human Services (2014); NIH Public Access Policy; http://publicaccess.nih.gov/policy.htm (accessed 23rd August 2015)

University of Glasgow (2016); Inspiring Economic Impact; available from http://www.gla.ac.uk/media/media_439420_en.pdf

University of Toronto (2013); Economic Impact Report; available from http://universityrelations.utoronto.ca/gicr/files/2013/07/economic-impact-2013.pdf

Uyarra, E (2010); *Conceptualizing the Regional Roles of Universities, Implications and Contradictions*; European Planning Studies **18**(8):1227-1246

Van Noorden, R, Maher, B & Nuzzo, R (2014); *The Top 100 Papers;* Nature **514** (7524): 550 – 553

Van Calster, B (2012); *It Takes Time: A Remarkable Example of Delayed Recognition*; Journal of the American Society for Information Science and Technology **63**(11):2341-2344

van Eck, NJ, Waltman, L, van Raan, AFJ, Klautz, RJM & Peul, WC (2013); *Citation Analysis May Severely Underestimate the Impact of Clinical Research as Compared to Basic Research*; PloS ONE **8**(4):e62395

van Genuchten, M & Hatton, L (2013); *Quantifying Software's Impact*; Computer **46**(10):66-72

van Leeuwen, TN, Visser, MS, Moed, HF, Nederhof, TJ & van Raan, AFJ (2003); *The Holy Grail of Science Policy: Exploring and Combining Bibliometric Tools in Search of Scientific Excellence*; Scientometrics **57**(2):257-280

van Raan, AFJ (2004); *Sleeping Beauties in Science*; Scientometrics **59**(3):467-472

van Raan, AFJ (2006); *Comparison of the Hirsch-Index with Standard Bibliometric Indicators and with Peer Judgment for 147 Chemistry Research Groups*; Scientometrics **67**(3):491-502

van Raan, AFJ (2015); *Dormitory of Physical and Engineering Sciences: Sleeping Beauties May Be Sleeping Innovations*; PloS ONE **10**(10):e0139786

Vásquez-Urragio, AR, Barge-Gil, A & Modrego Rico, A (2016); *Which Firms Benefit More from Being Located in a Science and Technology Park? Empirical Evidence for Spain*; Research Evaluation **25**(1):107-117

Venkatraman, SS (2011); *The Dark Green Side of Information Technology*; International Journal of Business Insights and Transformation **3**(S3):96-106

Verbeke, A, Bachor, V & Nguyen, B (2013); *Procedural Justice, Not Absorptive Capacity, Matters in Multinational Enterprise ICT Transfers*; Management International Review **53**(4): 535-554

Vieira, ES & Gomes, JANF (2016); *The Bibliometric Indicators as Predictors of the Final Decision of the Peer Review*; Research Evaluation **25**(2):170-183

Wainer, J, Eckmann, A, Goldenstein, S & Rocha, A (2013); *How Productivity and Impact Differ Across Computer Science Subareas*; Communications of the ACM **56**(8):67-73

Wallace, ML, Larivière, V & Gingras, Y (2009); *Modeling a Century of Citation Distributions*; Journal of Informetrics **3**(4):296-303

Walsh, JP, Lee, Y-N & Jung, T (2016); *Win, Lose or Draw? The Fate of Patented Inventions*; Research Policy **45**(7):1362-1373

Walt, G (1994); *How Far Does Research Influence Policy?*; European Journal of Public Health **4**(4): 233-235

Waltman, L & Costas, R (2014); *F1000 Recommendations as a Potential New Data Source for Research Evaluation: A Comparison with Citations*; Journal of the Association for Information Science and Technology **65**(3):433-445

Waltman, L, van Raan, AFJ & Smart, S (2014); *Exploring the Relationship Between the Engineering and Physical Sciences and the Health and Life Sciences by Advanced Bibliometric Methods*; PloS ONE **9**(10):e111530

Wang, G & Guan, J (2010); *The Role of Patenting Activity for Scientific Research: A Study of Academic Inventors from China's Nanotechnology*; Journal of Informetrics **4**(3): 338-350

Wang, J (2013); *Citation Time Window Choice for Research Impact Evaluation*; Scientometrics **94**(3):851-872

Wang, J, Ma, F, Chen, M & Rao, Y (2012); *Why and How Can "Sleeping Beauties" be Awakened?*; The Electronic Library **30**(1):5-18

Wang, J & Shapira, P (2015); *Is There a Relationship between Research Sponsorship and Publication Impact? An Analysis of Funding Acknowledgements in Nanotechnology Papers*; PloS ONE **10**(2): e0117727

Wardale, D & Lord, L (2016); *Bridging the Gap: The Challenges of Employing Entrepreneurial Processes within University Settings*; Higher Education Research & Development **35**(5):1068-1082

Waterman, RW & Meier, KJ (1998); *Principal-Agent Models: An Expansion?*; Journal of Administration Research and Theory **8**(2):173-202

Watson, D, Hall, L & Tazzyman, S (2016); *Trick or Treat: Academic Buy-in to Third Stream Activities*; Industry & Higher Education **30**(2):155-167

Watt, IJ (2015) Report of the Review of Research Policy and Funding Arrangements; Commonwealth of Australia; Canberra, Australia; ISBN: 978-1-76028-508-1;

Weingart, P (2005); *Impact of Bibliometrics Upon the Science System: Inadvertent Consequences?*; Scientometrics **62**(1):117-131

Whittington, KB & Smith-Doerr, L (2005); *Gender and Commercial Science: Women's Patenting in the Life Sciences*; Journal of Technology Transfer **30**(4): 355-370

Wilkinson, D, Sud, P & Thelwall, M (2014); *Substance Without Citation: Evaluating the Online Impact of Grey Literature*; Scientometrics **98**(2):797-806

Wilsdon, J, Allen, L, Belfiore, E, Campbell, P, Curry, S, Hill, S, Jones, R, Kain, R, Kerridge, S, Thelwall, M, Tinkler, J, Viney, I, Wouters, P, Hill, J & Johnson, B (2015); The Metric Tide: Report of the Independent Review of the Role of Metrics in Research Assessment and Management; HECFE; ISBN: 1902369273

Wilson, J (2016); *The Hidden Topography of Australia's Arts Nation*; Australian Universities' Review **56**(1):20-29

Wilson, R, Mack, J & Walsh, B (2013); *Stagnation, Decline and Gender Disparity in Participation in NSW HSC Mathematics and Science Combinations*; Proceedings of the Australian Conference on Science and Mathematics Education; 19 – 21 September 2013; Canberra, Australia; pp: 199-204; ISBN: 978-0-9871834-2-2

World Bank (2016); World Development Indicators 2016; World Bank; Washington DC, USA; ISBN: 978-1-4648-0683-4

World Economic Forum (2016); The Future of Jobs Employment, Skills and Workforce Strategy for the Fourth Industrial Revolution Executive Summary; available from http://www3.weforum.org/docs/WEF_FOJ_Executive_Summary_Jobs.pdf

(WIPO) World Intellectual Property Organization (2014); Patent Pools and Antitrust – A Comparative Analysis; available from http://www.wipo.int/export/sites/www/ip-competition/en/studies/patent_pools_report.pdf

Wittbrodt, BT, Glover, AG, Laureto, J, Anzalone, GC, Oppliger, D, Irwin, JL & Pearce, JM (2013); *Life-Cycle Economic Analysis of Distributed Manufacturing with Open-Source 3-D Printers*; Mechatronics **23**(6):713-726

Wong, PK & Singh, A (2010); *University Patenting Activities and Their Link to the Quantity and Quality of Scientific Publications*; Scientometrics **83**(1):271-294

Wooding, S, Van Leeuwen, TN, Parks, S, Kapur, S & Grant, J (2015); *UK Doubles Its "World Leading" Research in Life Sciences and Medicine in Six Years: Testing the Claim?*; PloS ONE **10**(7):e0132990

Woolgar, S (1991); *Beyond the Citation Debate: Towards a Sociology of Measurement Technologies and Their Use in Science Policy*; Science and Public Policy; **18**(5):319 – 326

World Bank (2015); World Development Indicators: Manufacturing, Value Added (% of GDP); http://data.worldbank.org/indicator/NV.IND.MANF.ZS

World Bank (2015); World Development Indicators*:* http://databank.worldbank.org/data/reports.aspx?source=2&Topic=14

World Management Survey (2009); Management Matters in Australia: Just How Productive are We? Findings from the Australian Management Practices and Productivity Global Benchmarking Project; Report commissioned by Department of Innovation, Industry, Science and Research; ISBN: 978 0 642 72626 1

Yang, C-H, Motohashi, K & Chen, J-R (2009); *Are New Technology-Based Firms Located in Science Parks Really More Innovative? Evidence from Taiwan;* Research Policy **38**(1): 77-85

Yegros-Yegros, A, Rafols, I & D'Este, P (2015); *Does Interdisciplinary Research Lead to Higher Citation Impact? The Different Effect of Proximal and Distal Interdisciplinarity*; PloS ONE **10**(8):e0135095

Yu, M-C, Wu, Y-C J, Alhalabi, W, Kao, H-Y. Wu, W-H (2016); *ResearchGate: An Effective Altmetric Indicator for Active Researchers?*; Computers in Human Behaviour **55**(Part B):1001-1006

Zahra, SA & George, G (2002); *Absorptive Capacity: a Review, Reconceptualization, and Extension*; The Academy of Management Review **27**(1): 185-203

Zolas, N, Goldschlag, N, Jarmin, R, Stephan, P, Owen-Smith, J, Rosen, RF, McFadden Allen, B, Weinberg, BA & Lane, JI (2015); *Wrapping it up in a Person: Examining Employment and Earnings Outcomes for PhD Recipients*; Science **350**(6266):1367-1371

Zoller, FA, Zimmerling, E & Boutellier, R (2014); *Assessing the Impact of the Funding Environment on Researchers' Risk Aversion: The Use of Citation Statistics*"; Higher Education **68**(3):333-345

Zuppo, CM (2012); *Defining ICT in a Boundaryless World: The Development of a Working Hierarchy*; International Journal of Managing Information Technology (IJMIT) **4**(3): 13-22

Zúñiga-Vicente, JA, Alonso-Borrego, C, Forcadell, FJ & Galán, JI (2014); *Assessing the Effect of Public Subsidies on Firm R&D Investment: A Survey*; Journal of Economic Surveys **28**(1):36-67

# Appendix 1: NICTA RHD Student Data

| Student Ref | Local/International | Initial Graduate Destination Type | Most Recent Graduate Destination Type | Most Recent Graduate Destination Location | Most Recent Graduate Destination ISIC Classification | Most Recent Graduate Destination ABS Industry Code | months since submission | Years since Submission |
|---|---|---|---|---|---|---|---|---|
| ♥001 | International | University | University | Vic | 8530 | 8102 | 13.17 | 1.08 |
| 002 | International | University | University | Vic | 8530 | 8102 | 25.33 | 2.08 |
| 003 | Local | University | University | Vic | 8530 | 8102 | 39.23 | 3.22 |
| 004 | Local | NFP | NFP | Vic | 7210 | 6910 | 80.03 | 6.58 |
| 005 | Local | University | University | VIC | 8530 | 8102 | 0.37 | 0.03 |
| 006 | International | University | University | Asia | 8530 | 8102 | 60.83 | 5.00 |
| 007 | International | University | SME | Australia | 6202 | 7000 | 71.47 | 5.87 |
| 008 | International | SME | SME | Vic | 6202 | 7000 | 62.87 | 5.17 |
| 009 | Local | NFP | NFP | Australia | 7220 | 6910 | 77.73 | 6.39 |
| 010 | Local | MNC | MNC | Vic | 7020 | 6962 | 58.60 | 4.82 |
| 011 | Local | University | University | North America | 8530 | 8102 | 76.40 | 6.28 |
| 012 | Local | University | University | Vic | 8530 | 8102 | 54.70 | 4.50 |
| 013 | Local | SME | SME | Vic | 5820 | 5420 | 29.70 | 2.44 |
| 014 | International | MNC | MNC | Asia | 6120 | 5802 | 58.00 | 4.77 |
| 015 | Local | University | University | Vic | 8530 | 8102 | 65.43 | 5.38 |
| 016 | Local | University | University | Vic | 8530 | 8102 | 76.80 | 6.31 |
| 017 | Local | MNC | MNC | Vic | 7490 | 6962 | 45.87 | 3.77 |
| 018 | Local | University | University | Vic | 8530 | 8102 | 47.30 | 3.89 |
| 019 | local | University | University | Asia | 8530 | 6910 | 45.77 | 3.76 |
| 020 | Local | University | University | Vic | 8530 | 8102 | 100.17 | 8.23 |
| 021 | Local | University | Start-up | Vic | 5820 | 5420 | 99.33 | 8.16 |
| 022 | Local | University | University | Vic | 8530 | 8102 | 90.67 | 7.45 |
| 023 | Local | PFRA | University | Vic | 8530 | 8102 | 41.43 | 3.41 |
| 024 | International | MNC | MNC | North America | 2610 | 7000 | 18.13 | 1.49 |
| 025 | International | PFRA | PFRA | Europe | 7210 | 6910 | 88.80 | 7.30 |
| 026 | International | NICTA (NFP) | NFP | Vic | 7210 | 6910 | 63.23 | 5.20 |
| 027 | International | University | University | Asia | 8530 | 8102 | 42.73 | 3.51 |
| 028 | Local | NFP | PFRA | Australia | 7210 | 6910 | 39.30 | 3.23 |
| 029 | International | University | University | Australia | 8530 | 8102 | 60.03 | 4.93 |
| 030 | International | MNC | MNC | Vic | 7210 | 6910 | 49.27 | 4.05 |
| 031 | International | PFRA | PFRA | Asia | 7210 | 6910 | 71.90 | 5.91 |
| 032 | International | University | University | Vic | 8530 | 8102 | 16.60 | 1.36 |
| 033 | International | MNC | MNC | Vic | 6202 | 7000 | 77.57 | 6.38 |
| 034 | Local | MNC | University | Middle East | 8530 | 8102 | 69.70 | 5.73 |
| 035 | Local | University | University | Vic | 8530 | 8102 | 49.27 | 4.05 |
| 036 | International | MNC | MNC | Vic | 7210 | 6910 | 15.20 | 1.25 |
| 037 | Local | Start-Up | Start-up | Asia | 3250 | 7000 | 56.37 | 4.63 |
| 038 | Local | University | University | Asia | 8530 | 8102 | 45.43 | 3.73 |
| 039 | Local | MNC | SME | Vic | 9200 | 9209 | 5.50 | 0.45 |
| 040 | International | MNC | MNC | Asia | 6619 | 6419 | 80.37 | 6.61 |
| 041 | International | NICTA (NFP) | PFRA | Australia | 7210 | 6910 | 30.93 | 2.54 |
| 042 | International | SME | SME | Vic | 6110 | 5809 | 31.07 | 2.55 |
| 043 | International | MNC | MNC | Vic | 2630 | 5809 | 89.40 | 7.35 |
| 045 | International | NICTA (NFP) | University | Vic | 8530 | 8102 | 26.43 | 2.17 |
| 046 | International | SME | MNC | Vic | 6492 | 6240 | 87.13 | 7.16 |
| 047 | Local | NICTA (NFP) | University | Vic | 8530 | 8102 | 83.17 | 6.84 |
| 048 | International | NFP | NfP | Vic | 7210 | 6910 | 32.47 | 2.67 |
| 049 | International | SME | SME | Vic | 6209 | 7000 | 5.77 | 0.47 |
| 050 | International | MNC | SME | Australia | 2651 | 2319 | 60.83 | 5.00 |
| 051 | International | MNC | SME | Vic | 6110 | 5809 | 99.03 | 8.14 |

| Student Ref | Local/International | Initial Graduate Destination Type | Most Recent Graduate Destination Type | Most Recent Graduate Destination Location | Most Recent Graduate Destination ISIC Classification | Most Recent Graduate Destination ABS Industry Code | months since submission | Years since Submission |
|---|---|---|---|---|---|---|---|---|
| 052 | Local | University | University | Vic | 8530 | 8102 | 81.00 | 6.66 |
| 053 | International | SME | SME | Vic | 6311 | 5921 | 23.90 | 1.96 |
| 054 | International | University | MNC | Vic | 2630 | 5809 | 34.47 | 2.83 |
| 055 | Local | MNC | MNC | Vic | 6312 | 5910 | 41.23 | 3.39 |
| 056 | International | University | University | Europe | 8530 | 8102 | 27.93 | 2.30 |
| 057 | Local | University | University | Vic | 8530 | 8102 | 34.57 | 2.84 |
| 058 | Local | Start-Up | University | Vic | 8530 | 8102 | 70.07 | 5.76 |
| 059 | International | NICTA (NFP) | Start-up | Vic | 6311 | 6999 | 85.20 | 7.00 |
| 060 | Local | NICTA (NFP) | Start-up | North America | 6612 | 6962 | 101.00 | 8.30 |
| 061 | International | NFP | MNC | Vic | 7210 | 6910 | 62.90 | 5.17 |
| 062 | International | University | University | Vic | 8530 | 8102 | 59.83 | 4.92 |
| 063 | Local | SME | SME | Australia | 3250 | 2599 | 12.17 | 1.00 |
| 064 | International | SME | SME | Vic | 2930 | 2313 | 38.33 | 3.15 |
| 065 | Local | NICTA (NFP) | SME | Asia | 6110 | 2429 | 80.53 | 6.62 |
| 066 | Local | University | University | Vic | 8530 | 8102 | 77.63 | 6.38 |
| 067 | International | Start-Up | Start-up | Vic | 7990 | 7220 | 7.07 | 0.58 |
| 068 | International | Government | Government | Asia | 6110 | 5809 | 61.87 | 5.08 |
| 069 | Local | NICTA (NFP) | University | Europe | 8530 | 8102 | 48.37 | 3.98 |
| 070 | Local | NICTA (NFP) | MNC | Vic | 7210 | 6910 | 37.17 | 3.05 |
| 071 | International | SME | SME | Vic | 5820 | 5420 | 45.80 | 3.76 |
| 072 | International | SME | MNC | Vic | 7020 | 6962 | 86.67 | 7.12 |
| 073 | International | NICTA (NFP) | Start-up | Vic | 7110 | 6924 | 72.23 | 5.94 |
| 074 | International | University | University | Vic | 8530 | 8102 | 33.07 | 2.72 |
| 075 | International | SME | SME | Vic | 6110 | 5809 | 96.70 | 7.95 |
| 076 | International | NICTA (NFP) | University | Vic | 8530 | 8102 | 14.37 | 1.18 |
| 077 | International | NICTA (NFP) | MNC | Vic | 2630 | 2429 | 68.07 | 5.59 |
| 078 | Local | University | University | Asia | 8530 | 8102 | 71.73 | 5.90 |
| 079 | Local | University | University | Australia | 8530 | 8102 | 39.70 | 3.26 |
| 080 | Local | University | Start-up | Vic | 3250 | 2599 | 52.60 | 4.32 |
| 081 | International | University | University | Vic | 8530 | 8102 | 50.00 | 4.11 |
| 082 | Local | SME | SME | Vic | 6311 | 5921 | 107.20 | 8.81 |
| 083 | International | MNC | MNC | Europe | 2630 | 2422 | 45.17 | 3.71 |
| 084 | International | NICTA (NFP) | NFP | Vic | 7210 | 6910 | 16.10 | 1.32 |
| 085 | International | SME | SME | Vic | 7110 | 6923 | 90.60 | 7.45 |
| 086 | International | NICTA (NFP) | MNC | Vic | 6419 | 6221 | 92.20 | 7.58 |
| 087 | International | NFP | NFP | Vic | 7210 | 6910 | 41.87 | 3.44 |
| 088 | International | NICTA (NFP) | NFP | Vic | 7210 | 6910 | 47.67 | 3.92 |
| 089 | International | NICTA (NFP) | Government | Middle East | 8413 | 7000 | 49.77 | 4.09 |
| 090 | International | University | University | Australia | 8530 | 8102 | 88.60 | 7.28 |
| 091 | International | NICTA (NFP) | Government | Vic | 8413 | 7520 | 51.43 | 4.23 |
| 092 | International | University | University | Vic | 8530 | 8102 | 44.50 | 3.66 |
| 093 | Local | University | University | Europe | 8530 | 8102 | 33.37 | 2.74 |
| 094 | International | NICTA (NFP) | Start-up | Vic | 7110 | 6924 | 79.17 | 6.51 |
| 095 | International | University | University | Vic | 8530 | 8102 | 63.87 | 5.25 |
| 096 | International | SME | SME | Vic | 3510 | 5922 | 67.93 | 5.58 |
| 097 | Local | MNC | MNC | Vic | 7490 | 6962 | 72.47 | 5.96 |
| 098 | Local | MNC | MNC | Vic | 6492 | 6240 | 98.40 | 8.09 |
| 099 | International | University | University | Vic | 8530 | 8102 | 44.90 | 3.69 |
| 100 | Local | University | MNC | North America | 5820 | 5420 | 107.70 | 8.85 |
| 101 | International | SME | SME | Vic | 3250 | 2599 | 70.03 | 5.76 |
| 102 | Local | University | MNC | North America | 3250 | 2599 | 74.80 | 6.15 |
| 103 | International | University | University | Vic | 8530 | 8102 | 21.27 | 1.75 |
| 104 | International | NFP | NFP | Vic | 7210 | 6910 | 40.40 | 3.32 |

| Student Ref | Local/International | Initial Graduate Destination Type | Most Recent Graduate Destination Type | Most Recent Graduate Destination Location | Most Recent Graduate Destination ISIC Classification | Most Recent Graduate Destination ABS Industry Code | months since submission | Years since Submission |
|---|---|---|---|---|---|---|---|---|
| 105 | International | NICTA (NFP) | NFP | Vic | 7210 | 6910 | 46.10 | 3.79 |
| 106 | International | SME | SME | North America | 5820 | 5420 | 9.10 | 0.75 |
| 107 | International | University | University | Vic | 8530 | 8102 | 19.23 | 1.58 |
| 108 | International | PFRA | MNC | Vic | 7210 | 6910 | 67.10 | 5.52 |
| 109 | Local | NICTA (NFP) | MNC | Australia | 0990 | 1892 | 80.03 | 6.58 |
| 110 | International | SME | SME | Vic | 6313 | 5910 | 30.50 | 2.51 |
| 111 | Local | NFP | NFP | Vic | 7210 | 6910 | 51.23 | 4.21 |
| 112 | Local | University | Government | Australia | 8411 | 7510 | 82.73 | 6.80 |
| 113 | International | University | University | Vic | 8530 | 8102 | 47.17 | 3.88 |
| 114 | International | NICTA (NFP) | Start-up | Vic | 7110 | 6924 | 72.70 | 5.98 |
| 115 | Local | NICTA (NFP) | SME | Vic | 7410 | 6999 | 66.20 | 5.44 |
| 116 | International | University | University | North America | 8530 | 8102 | 97.40 | 8.01 |
| 117 | International | Government | MNC | Vic | 7020 | 6962 | 78.67 | 6.47 |
| 118 | Local | NICTA (NFP) | Start-up | Vic | 7110 | 6924 | 69.80 | 5.74 |
| 119 | Local | University | MNC | Vic | 6419 | 6221 | 83.70 | 6.88 |
| 120 | International | University | University | Vic | 8530 | 8102 | 14.20 | 1.17 |

University Library

MINERVA ACCESS

A gateway to Melbourne's research publications

Minerva Access is the Institutional Repository of The University of Melbourne

**Author/s:**
McLeod, Annette

**Title:**
Returns on investment: considerations on publicly funded ICT research and impact assessment

**Date:**
2016

**Persistent Link:**
http://hdl.handle.net/11343/124272

**File Description:**
Thesis: Returns on Investment: Considerations on Publicly Funded ICT Research and Impact Assessment

**Terms and Conditions:**
Terms and Conditions: Copyright in works deposited in Minerva Access is retained by the copyright owner. The work may not be altered without permission from the copyright owner. Readers may only download, print and save electronic copies of whole works for their own personal non-commercial use. Any use that exceeds these limits requires permission from the copyright owner. Attribution is essential when quoting or paraphrasing from these works.