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Australian Academy of Science

THE IMPORTANCE OF ADVANCED PHYSICAL AND MATHEMATICAL SCIENCES TO THE AUSTRALIAN ECONOMY

MARCH 2015

Prepared by the Centre for International Economics for the Office of the Chief Scientist and the Australian Academy of Science.

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FOREWORD

The contribution of science to the Australian economy, particularly the advanced physical and mathematical sciences covered in this report, is easy to take for granted. Indeed, because science is so important to every modern economy, we easily adjust our expectations and, paradoxically, the role of science becomes invisible to us.

In commissioning the work reported here, we have sought to combine the expertise of Australia's scientific community with that of business and industry. The aim has been to produce an economic framework that can use the available statistics and economic modelling techniques to provide a timely reminder of how much of our national economic activity depends on the advanced physical and mathematical sciences.[1]

In doing this work, the Centre for International Economics (CIE) has taken a rigorous, but conservative, approach to estimating the impact of the advanced physical and mathematical sciences.

The report estimates that the direct contribution of the advanced physical and mathematical sciences is equal to 11% of the Australian economy (that is, about $145 billion per year). Along with the direct contribution, the report estimates additional and flow-on benefits of another 11%, bringing total benefits to just over 22% (around $292 billion per year). Importantly, the report points out that this estimate of the contribution of advanced physical and mathematical sciences is likely to be conservative, and sets out several other areas of benefit that are harder to measure.

This report carefully considers the pathways by which the advanced physical and mathematical sciences yield economic benefits. Thinking about those pathways shows that the Australian community's continuing commitment to the advanced physical and mathematical sciences will be needed to ensure that the benefits from what is essentially a global scientific enterprise can accrue to the Australian economy. We expect that similar comments would apply to other sciences not yet considered in this type of work.

The message is clear, however: without strong local commitment to science, it will not be possible to translate scientific developments into economic gains for Australia. With that commitment, all Australians will benefit.

ABOVE LEFT:
Australia's Chief Scientist,
Professor Ian Chubb AC

ABOVE RIGHT:
Professor Andrew Holmes AM PresAA FRS FTSE
President
Australian Academy of Science

1 We expect that future work will also clarify and measure the contributions of biology and other life sciences.

ACKNOWLEDGEMENTS

The CIE thanks Professor Ian Chubb (Australia's Chief Scientist) and Dr Sue Meek (CEO of the Australian Academy of Science (the Academy)) for commissioning this research and for their support throughout the project. In addition, Dr Roslyn Prinsley and Dr Krisztian Baranyai (from the Office of the Chief Scientist) provided excellent analytical and practical support throughout the analysis. Dr Poulomi Agrawal and Nancy Pritchard (from the Academy) helped keep the project on target in many practical ways.

The analysis in this report would not have been possible without the contributions and enthusiasm of the Australian scientists who attended the workshop, run by the Academy and the CIE, that was the foundation for the report. We also thank the individuals, from a wide range of industry organisations, who engaged in discussions to test the views of the scientists.

The CIE also acknowledges the large contribution made to this study by Professor Hans Bachor FAA (The Australian National University, Chair—the Academy's National Committee for Physics) who advised on many scientific matters.

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THE ADVANCED PHYSICAL AND MATHEMATICAL SCIENCES—
underpinning Australian economic activity and worth $292 billion each year

Physics, chemistry, the earth sciences and mathematics help to support our national wealth.

We need to continue our national commitment to the advanced* physical and mathematical sciences if we are to recognise opportunities and capture the rewards. It is of substantial economic benefit.

There is a lot at stake.

*Advanced means science undertaken and applied in the past 20 years.

11%

11% of Australian economic activity relies directly on the advanced physical and mathematical sciences.

22%

The total direct and flow-on impact of the advanced physical and mathematical sciences sector amounts to over 22% of Australian economic activity, or about **$292 billion per year.**

760K

7% of total Australian employment (about 760 000 jobs) is directly related to the advanced physical and mathematical sciences.

$145b

The direct contribution of the advanced physical and mathematical sciences to the economy is around $145 billion per year.

75%

Labour productivity of workers in the advanced physical and mathematical sciences is estimated to be 75% greater than workers in the rest of the economy.

$74b

Exports associated with the advanced physical and mathematical science activities are worth around $74 billion a year. This is 28% of Australia's goods exports and equivalent to 23% of total Australian exports of goods and services.

SUMMARY

This report examines all the sectors in the Australian economy from the bottom up to estimate the importance of the advanced physical and mathematical sciences (the APM sciences) to the Australian economy.

The APM sciences are the core physical sciences of physics, chemistry, the earth sciences and the mathematical sciences. 'Advanced' means science first applied in the past 20 years. Biology and the life sciences are not covered in this report.

THE TOTAL IMPACT OF THE ADVANCED PHYSICAL AND MATHEMATICAL SCIENCES (APM SCIENCES) ON THE ECONOMY

Figure 1 shows the direct, flow-on and total impacts of the APM sciences on the economy, measured as their share of economy-wide activity—that is, as their share of gross value added (GVA) in the economy and in billions of dollars per year. The 'low' and 'high' values delineate the uncertainty about the 'middle' estimates of the impacts.

The reasoning and analysis behind these results are set out in more detail below.

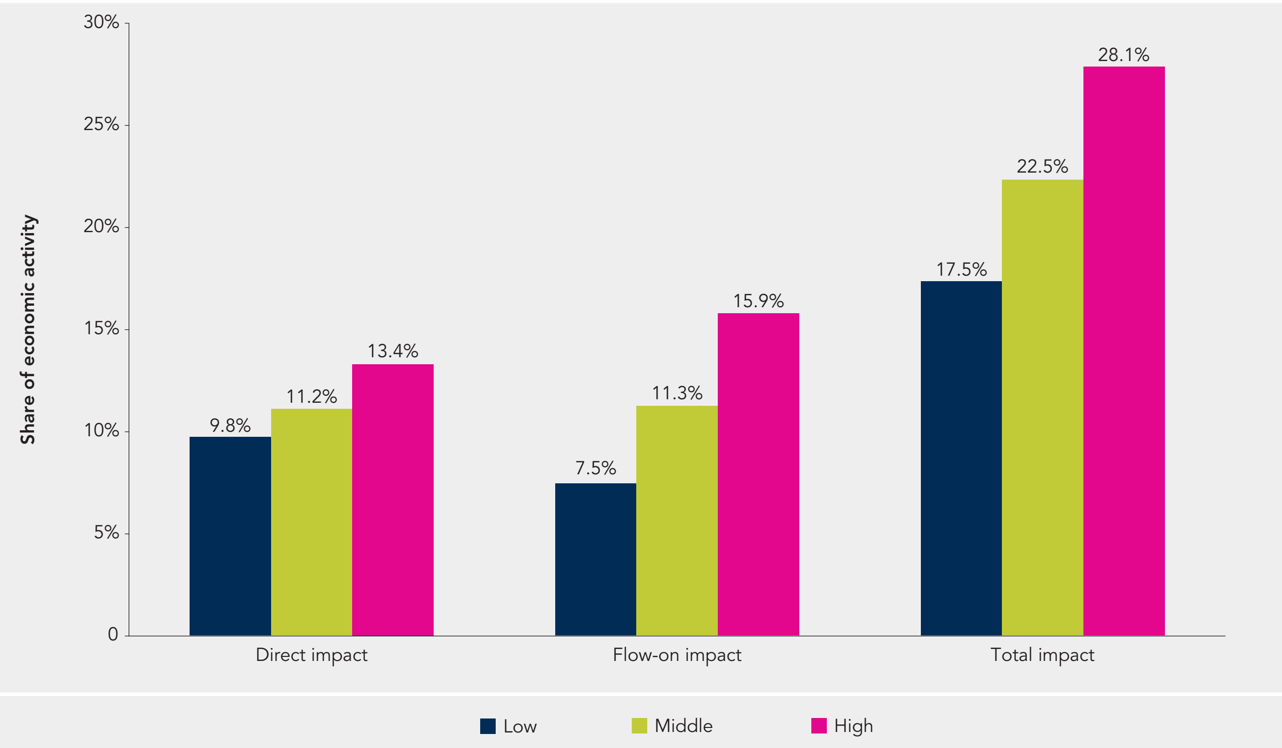
The direct impact of the APM sciences

The APM sciences have a *direct* impact on the economy, as they are the source of useful knowledge that is embodied in economic inputs (labour, capital and systems) that businesses use to produce output. The APM sciences allow output to be greater than it would have been in their absence.

As shown in Figure 1, we estimate that $145 billion worth of GVA in the Australian economy (or 11.2% of the economy) each year is produced using inputs based on the APM sciences. This is our estimate of the direct impact of the APM sciences on the economy.

This result was calculated from the bottom up. To do this, the Australian Academy of Science (the Academy) and the Centre for International Economics (the CIE) staged a two-day workshop for APM scientists representing the national committees for science of the Australian Academy of Science (the Academy). We then conducted follow-up industry consultations to determine separately the importance of the APM sciences to all 506 industry classes in the ANZSIC 2006 industry classification system. Table 1 lists the top 10 industry groups identified and the GVA and APM sciences share for each of the industry classes (full details for all classes are in Appendix 1 of this report).

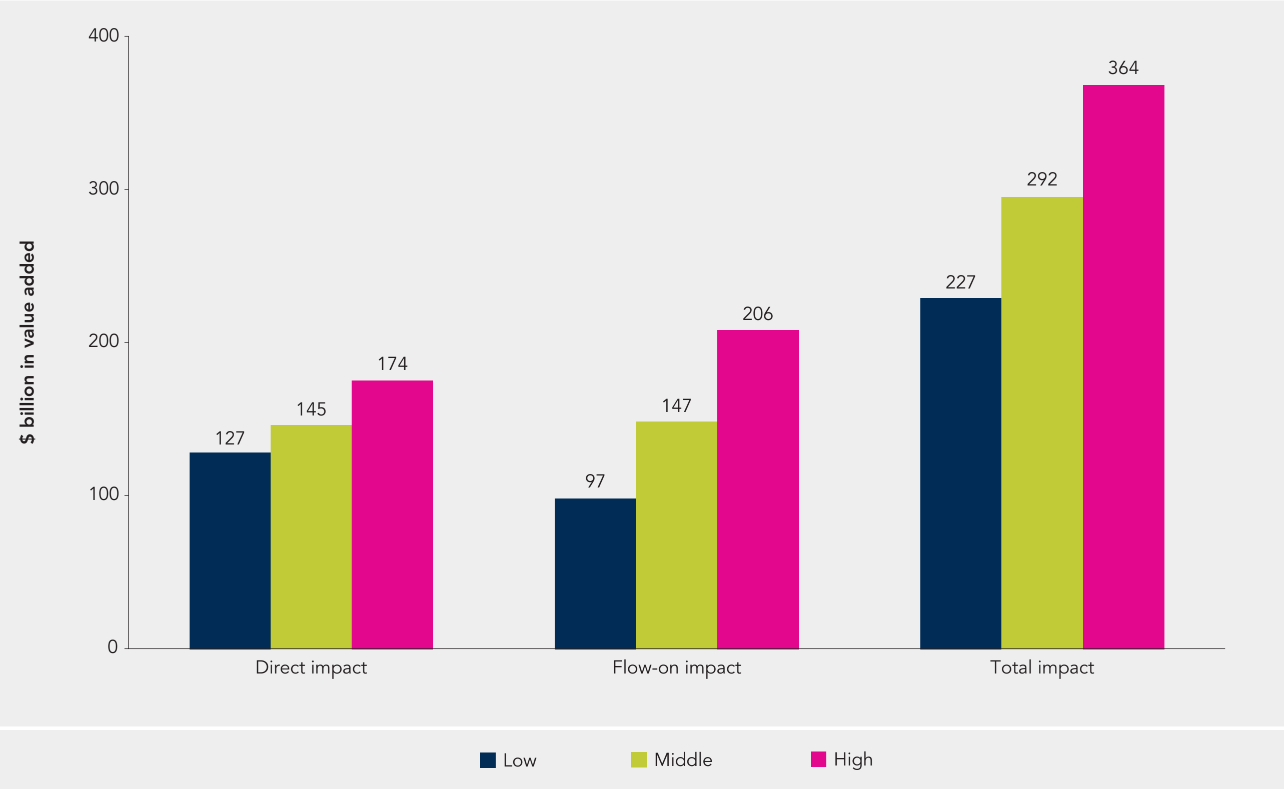
Figure 1 The direct, flow-on and total impacts of the APM sciences on the Australian economy (% share of economic activity, $ billion value added)



Note: To express APM sciences based GVA as a share of total GVA, we have excluded from the total the GVA of the *ownership of dwellings* industry, as it is imputed by the ABS and the industry does not employ any people (it makes up 9% of the total).

Data source: The CIE.

Figure 1 (continued) The direct, flow-on and total impacts of the APM sciences on the Australian economy (% share of economic activity, $ billion value added) continued



Note: To express APM sciences based GVA as a share of total GVA, we have excluded from the total the GVA of the *ownership of dwellings* industry, as it is imputed by the ABS and the industry does not employ any people (it makes up 9% of the total).

Data source: The CIE.

Table 1 Gross value added by the APM sciences, by industry class, 2012–13

Industry classes		Total GVA	APM sciences based GVA	APM sciences share
		$b, current prices	$b, current prices	%
700	Oil and Gas Extraction	32	16	50.0
6322	General Insurance	19	8	40.0
801	Iron Ore Mining	23	7	30.0
804	Gold Ore Mining	17	7	40.0
5801	Wired Telecommunications Network Operation	16	7	40.0
8520	Pathology and Diagnostic Imaging Services	5	5	100.0
6221	Banking	54	5	10.0
7000	Computer System Design and Related Services	24	5	20.0
5802	Other Telecommunications Network Operation	7	4	60.0
4610	Road Freight Transport	19	4	20.0
Total of other science-based industry classes		325	78	23.9
Total of science-based sector		540	145	26.8

Source: ABS; The CIE.

The flow-on and total impacts of the APM sciences

We estimated the flow-on and total impacts of the APM sciences using a 'general equilibrium' or economy-wide model of the Australian economy.

The flow-on effects arise because the direct output of industries based on the APM sciences is subsequently purchased by other industries, exporters and consumers. Because the APM sciences allow increased output in one group of industries, there are indirect consequences for all other industries in the economy.

Importantly, we assumed that the direct impact of the APM sciences is to allow a productivity improvement in the activities that use those sciences. This mirrors the way that the effect of the APM sciences works in the economy.

We used information on the magnitude of the direct impact within each industry to simulate the total flow-on effects throughout the economy.

In this model, other industries that use the output of industries based on the APM sciences effectively experience a price reduction in input costs and can expand their own production.

Consumers who use output based on the APM sciences also make savings, some of which are used to boost consumption elsewhere in the economy. The additional economic output that is created by these business gains and consumer savings is the flow-on impact of the APM sciences.

We estimate that this impact is equivalent to $147 billion of GVA per year, or 11.3% of Australia's economic output.

Given these results, the total impact of the APM sciences on the economy is estimated to be equivalent to $292 billion worth of GVA per year, or 22.5% of output.

An illustration of the total impact of APM sciences on the economy

The telecommunications sector can be used to illustrate the total impact of APM sciences.

Advanced mathematics and physics provide the knowledge that underpins the provision of some telecommunications services, including mobile phones and wireless internet. The direct impact of this knowledge is the value of such services sold by telecommunications companies.

Advanced telecommunications services increase the effectiveness and efficiency with which businesses and consumers communicate. This creates productivity gains and consumer savings, which boost output. This is the flow-on impact of the APM sciences underpinning advanced telecommunications.

We should also consider what the economy would be like *without* advanced telecommunications services. In such an economy, we would be forced to communicate using fixed-line telephones and postal services: we would miss out on the productivity gains and consumer savings arising from the APM sciences.

Uncertainty associated with the results

It is difficult to estimate precisely the share of output that is produced using inputs that embody APM scientific knowledge. The CIE has considered this uncertainty. While our estimate is that the most likely magnitude of the direct impact of the APM sciences on the economy is equivalent to 11.2% of output, our analysis suggests that the true magnitude lies somewhere in the range from 9.8% of output to 13.4% of output.

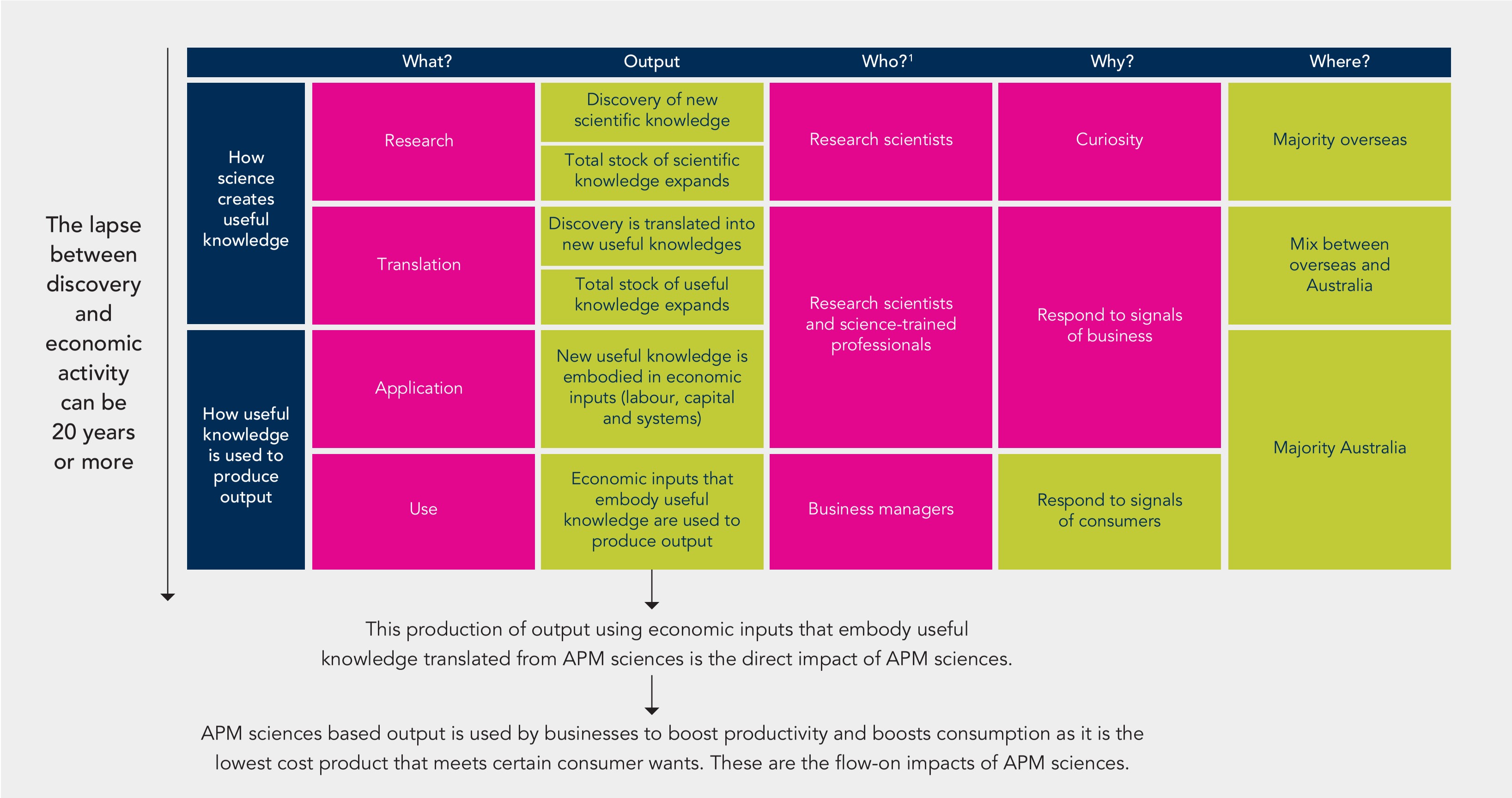
This uncertainty about the direct impact flows into our estimate of the flow-on impact, which we determined using the CIE-REGIONS CGE model (see Appendix 2 of this report). As in any economic model, there is some uncertainty associated with the results. Given these two factors, while the most likely magnitude of the flow-on impact of the APM sciences is equivalent to 11.3% of output, our analysis of the data shows that the true magnitude lies somewhere in the range from 7.5% of output to 15.9% of output.

While the most likely magnitude of the total impact of APM sciences on the economy is equivalent to 22.5% of output, we think that the true magnitude of that impact lies between 17.5% of output and 28.1% of output. Figure 1 shows these results.

HOW USEFUL APM KNOWLEDGE IS CREATED AND EMBODIED IN INDUSTRIAL INPUTS

Advanced scientific knowledge is discovered by research scientists, who are often motivated by their own curiosity. It is translated into 'useful' knowledge and then applied to economic inputs. This is done by research scientists and science-trained professionals, who are responding to signals from business. Business managers then use the economic inputs to produce output, in response to signals from consumers.

Figure 2 How science affects the economy



1 Research scientists, science-trained professionals and business managers should not be thought of as independent groups of people. Science-trained professionals can have strong links to research. Further, in sectors of the economy where science is crucial, business managers often have backgrounds in science. For example, many senior managers in mining companies started out as geologists.

Source: The CIE.

This process is illustrated in Figure 2, which also shows *where* these steps are likely to occur. As a relatively small advanced economy, Australia is a net importer of science (most of the research that we benefit from occurs overseas). However, crucial steps in the process require inputs from Australian science, including the translation of science knowledge into useful knowledge, the application of useful knowledge to economic inputs and the use of those inputs. This is mainly because many of the problems that Australia faces and that can be solved by science are at least slightly different from problems overseas. This means that most of the useful knowledge that we apply needs at least some input from Australians, who are familiar with our challenges; we cannot take our science 'off the shelf'.

Within the APM sciences, what is the source of useful knowledge?

Science, by its nature, is multidisciplinary. While an outsider might consider the science disciplines to be distinct fields that operate independently, scientists are continuously combining principles from multiple disciplines to solve problems and advance knowledge.

This means there are three distinct sources of useful knowledge.

- The core disciplines (mathematics, physics and chemistry) can provide useful knowledge individually. For example, part of the banking industry relies on complex mathematically based models that support risk and investment decisions, but on no other science input. We estimate that 3.6% of Australia's economic output is produced from inputs that embody useful knowledge from a single core discipline.
- Principles from the core disciplines have been combined to make new, 'non-core' disciplines that have become separate research fields and separate sources of useful knowledge. For Australia, the earth sciences (which are based on the principles of all three core disciplines) are an important non-core discipline, as they will underpin future mineral discoveries. We estimate that 0.3% of Australia's economic output is produced from inputs that embody useful knowledge from just the earth sciences.
- Principles from multiple disciplines can be combined to solve problems and create useful knowledge. For example, in the 1980s and 1990s, the Australian scientists who invented the technology that became Wi-Fi did so using mathematics to solve a physics problem. To transmit data wirelessly using radio waves (a physics problem), they had to manage interference from various sources, which they did by using a complicated mathematical algorithm. We estimate that 7.3% of Australia's economic output is produced from inputs that embody useful knowledge from multiple disciplines.

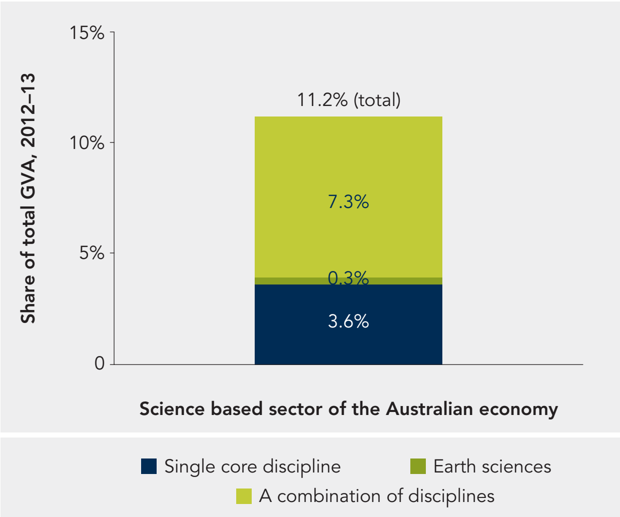
The multidisciplinary nature of science means that the total impact of science is greater than the sum of the contributions of the individual sciences. This is an important observation that must be understood to properly evaluate current science research efforts. For example, following the points made above, if a mathematician were to invent a new algorithm that allows more powerful mathematical models to be computed, that invention could advance the work of:

- mathematicians running models in banking
- earth scientists trying to find new minerals
- physicists in telecommunications trying to advance Wi-Fi.

It is possible that the benefit that would flow from the mathematician's work would be significant indeed.

Figure 3 shows the disciplines within the APM sciences that generate the useful knowledge underpinning 11.2% of Australian economic activity. Most of that activity is based on knowledge that is created by combining knowledge from different disciplines.

Figure 3 The source of useful APM scientific knowledge, by discipline, 2012–13 (% of total GVA)



Note: To express APM sciences based GVA as a share of total GVA, we excluded from the total the GVA of the *ownership of dwellings* industry, as it is imputed by the ABS and the industry does not employ any people (it makes up 9% of the total).

Data source: The CIE.

OUR RESULTS UNDERSTATE THE IMPACT OF THE APM SCIENCES

The results reported here almost certainly understate the true impact of the APM sciences.

Direct impact

We have estimated the direct impact of APM sciences on the economy by estimating the share of output that is produced using inputs that embody useful knowledge from the APM sciences. We took that approach because it was tractable.

However, our approach probably underestimates the true direct impact of the APM sciences because those sciences create various direct impacts that are *not* picked up in current output:

- Some APM science is aimed at developing economic resources and thus underpins *future* (rather than current) output. We have allowed for this by considering science from the past 20 years, but this is imprecise.
- Some APM science is aimed at improving health and safety and avoiding disasters, and thus at avoiding a loss of output rather than creating new output. The impact of this work cannot really be observed in current output. For example, what is the impact of Australia's tsunami warning system? Under our methodology, the impact of that invention is zero.
- Some APM science underpins regulations that, if justified, create a benefit that is not observed in current activity.
- Some APM science is used to create new consumer products (such as smartphones and better computers), the true direct impact of which is increased consumer utility. However, observed expenditure on such consumer products (what we measure) usually grows *slowly* compared with consumer pleasure (the true impact) because price growth tends to be constrained by production advances. This means that we are not picking up the full impact.
- Some APM science is aimed at optimising the use of resources or saving resources. If required investment in the economy falls as a result of that work, the true benefit is missed by considering (only) current output.

Flow-on impact

To measure the magnitude of the flow-on impact of APM sciences, we estimated the productivity gains and savings that *users* of APM sciences output get from that use.

However, some advances in the APM sciences do not merely save users' resources, but allow users to transform the way they use their resources. This is a profound and lasting flow-on impact that our model does not pick up. Therefore, it is likely that, overall, our estimate of the flow-on impact understates the true impact.

For example, in the case of Wi-Fi, the flow-on impact that we measure is the simple efficiencies and productivity gains created by switching from connecting to the internet via cables to connecting via radio waves. However, over time, wireless technology is transforming the way businesses and consumers behave, and the magnitude of that impact is far more than just an efficiency or a saving.

THE APM SCIENCES AND FOREIGN TRADE

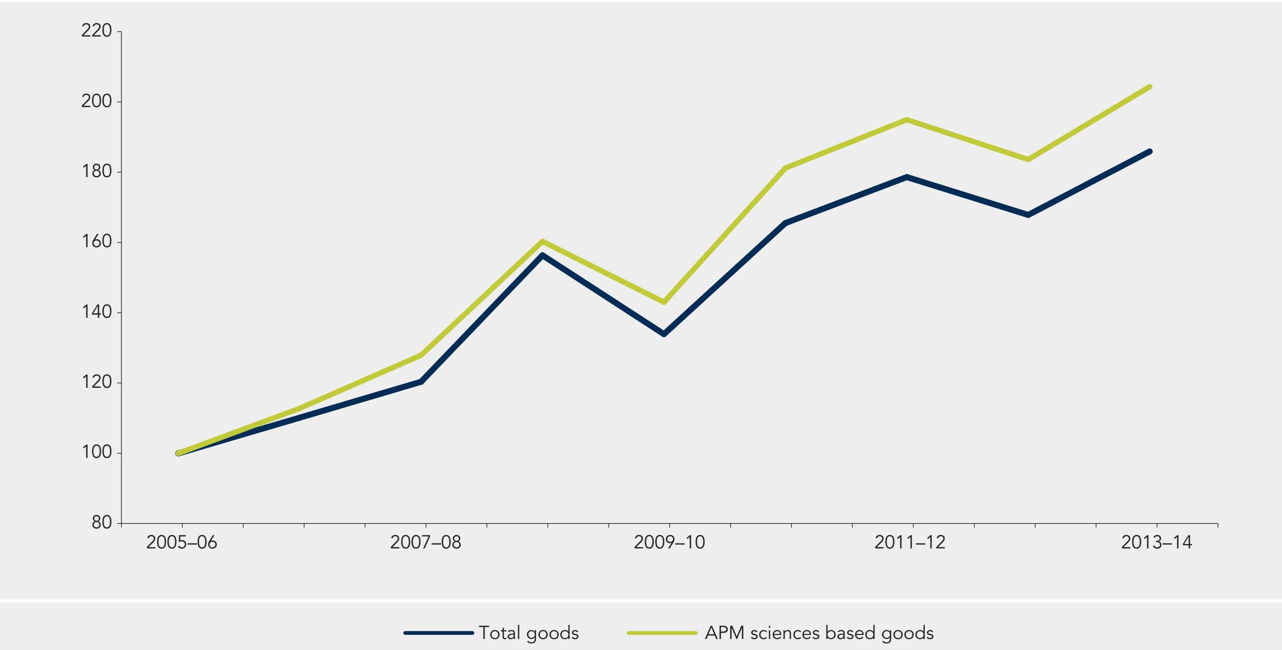
The APM sciences are very important (if not critical) to key parts of Australia's trade-exposed industries: agriculture, mining and manufacturing. Useful knowledge from the APM sciences allows those industries to use our natural resources and our capital to respond to growth in global demand, and to create exports that foreigners want to buy. It also provides the technology that supports competitiveness in those industries. Figure 4 shows that growth in exports of goods based on the APM sciences has been much stronger than total growth in goods exports.

IS AUSTRALIAN SCIENCE A LONG-RUN DRIVER OF AUSTRALIAN GROWTH?

Economists accept that, as a source of new ideas, useful knowledge and technical progress, science is an important long-run driver of economic growth and living standards in Australia.

However, because science knowledge flows easily across borders it is reasonable to ask: Why should we pay for research ourselves? Why can't we just import foreign-produced research?

Figure 4 Australian exports, 2005–06 to 2013–14 (index: 2005–06 = 100)



Data source: The CIE.

To answer those questions, we should consider two points. First, as outlined above, the new knowledge created by science research must be translated into useful knowledge. While the translation process will vary from case to case, Australian scientists will usually be required to translate the research of foreigners into knowledge that is useful for Australian consumers and businesses.

Second, given the pool of global science research that is available, the group of people charged with translating foreign science research into knowledge that is useful for Australians will have to evaluate different pieces of work and select the most promising ones *before* they start the translation. Given this, we must ask: What skills are needed to evaluate and select science research? How do we produce people who have those skills?

Generally, the skills of science-trained professionals are necessary to take the research of someone from outside Australia, decide that the work is appropriate or promising for Australia, and then translate it into knowledge that is useful for us. This is an important and subtle point. It means that, when evaluating Australian science, we must consider not only the value of research discoveries and solutions that are created here, but also consider whether Australian science acts as a necessary and efficient mechanism through which foreign research discoveries and solutions are accessed and applied here.

THERE IS A LOT AT STAKE

Between 17.5% and 28.1% of economic activity (the estimate reported in Figure 1) is a significant proportion at a single point in time. While our estimates represent a historical snapshot, it is reasonable to infer that a future without continued scientific development would involve lower economic growth simply because the proportion of growth that would otherwise come from growth in knowledge would be reduced.

While the exact magnitude of that reduction (in terms of annual growth, for example) cannot be inferred from our estimates, a 17.5%–28.1% reduction over a period of at least 20 years would be a substantial potential loss.

Australia must avoid that loss.

CHAPTER 1

1. INTRODUCTION

The Office of the Chief Scientist and the Australian Academy of Science (the Academy) commissioned the Centre for International Economics (the CIE) to measure the importance of the advanced physical and mathematical sciences (the APM sciences) to the Australian economy.

THIS REPORT

The approach and findings from our research are set out in this report as follows.

Chapter 1 sets out the aspects of science covered in our analysis and provides a broad overview of the conceptual framework that guided the analysis.

Chapter 2 explains how the APM sciences affect the economy.

Chapter 3 provides a number of case studies that illustrate how the APM sciences affect the economy and the general findings of the analysis in more detail.

Chapter 4 briefly reviews the broader literature on this topic, as our analysis builds on similar research undertaken in Europe and the United States. We note lessons from previous research that we applied in the current study.

Chapter 5 sets out the details of the methodology adopted for this study.

Chapter 6 reports our findings on the direct impact of the APM sciences on the Australian economy.

Chapter 7 takes the findings reported in Chapter 6 and uses an economic modelling framework to estimate the flow-on and total impacts of the APM sciences on the Australian economy.

Chapter 8 looks at the way that the disciplines within the APM sciences contribute to the overall direct impact of science, noting the importance of combinations of disciplines in generating the overall results.

Chapter 9 comments on the strengths and limitations of our methodology and results.

Chapter 10 makes some broad comparisons between economic outcomes in sectors based on the APM sciences and economic outcomes in other sectors of the economy.

Chapter 11 draws some broad conclusions about the importance of the APM sciences for future economic growth.

THE SCIENCES COVERED IN THIS REPORT

The focus of this report is on the APM sciences, which consist of physics, chemistry, the earth sciences and the mathematical sciences.

Core sciences

The mathematical sciences, physics and chemistry are among the 'core disciplines' of science. They provide a large body of knowledge and knowledge 'building blocks' that have been combined to make new, independent disciplines.

Earth sciences

The earth sciences include geology and related fields, but are considered in this report as a group.

The earth sciences are an example of independent disciplines that have been created by combining the principles of the core sciences (in this sense, they are not 'core'). Because the earth sciences provide the knowledge needed to discover and extract mineral resources, they are an important example (for Australia) of the combination of principles within science to create new knowledge.

Biology and the other life sciences

Biology and the other life sciences are not covered in this report. These disciplines are important and underpin a large amount of economic activity that is separate from the economic activity that is measured in this report. For this reason, it was judged that they deserve their own separate report.

Advanced science

Within the mathematical sciences, physics, chemistry and the earth sciences, this study considers only 'advanced' science. As a broad guide, this is defined as scientific knowledge based on research that goes beyond the traditional science taught in professional and vocational courses. It is the contemporary knowledge that allows companies to stay at the forefront of their industries and to create new business opportunities. Broadly, it is research undertaken and applied in the past two decades.

Finally, our analysis was not limited to Australian science. We also considered science and research that are undertaken overseas in cases where they creates useful knowledge that is then applied within the Australian economy.

CONCEPTUAL FRAMEWORK: WHAT THIS STUDY SOUGHT TO MEASURE

It is widely agreed that economic growth is driven by a number of factors, including:

- investment (increases in the capital stock)
- gains from trade (or commercial expansion)
- scale effects (arising, for example, from population growth)
- increases in the stock of human knowledge (associated with, but not limited to, science), which allow productivity improvements and the development of novel and improved products (see, for example Mokyr 1990, 2002, 2014).

Over the longer term, new knowledge is the dominant factor driving economic growth. As the American Academy of Arts and Sciences has recently noted:

> Basic research lies behind every new product brought to market, every new medical device or drug, every new defence and space technology, and many innovative business practices. To match the increasing pace of technological advancement across the globe, the United States must accelerate both the discovery of new scientific knowledge and the translation of that knowledge to useful purpose. (AAAS 2014, p. 11)

What is true for the United States is, of course, true for Australia. Consistent with this broad statement by the American Academy, economists accept that continued economic growth will require future scientific and technological development, that new knowledge has been a fundamental driver of growth in the past and that it will remain so, perhaps ever more so (see, for example, Mokyr 2014, Cowen 2011, Brynjolfsson and McAfee 2014). Without ongoing increases in human knowledge (including technical progress), any of the other factors driving economic growth will eventually encounter diminishing returns, and growth will slow.

However, it is difficult to translate these broad notions into precise quantitative measures of the current and future importance of the sciences to the Australian economy. The ways in which knowledge grows and then contributes to economic growth are complicated, dependent on circumstances and mediated by a wide variety of institutional and other factors. The clearest narratives of the importance of science are provided by economic historians (particularly in discussions about the industrial revolution), but those narratives also illustrate the complexity of interactions between knowledge and other factors.[1] The academic disciplines of economics, economic history and the history of technology are still working to clarify those interactions. For this report, some simplification is needed.

Figure 1.1 is a schematic illustration of these points. It shows specifically what this study sought to measure (and what it did not). Gross domestic product (GDP) depends on the stock of knowledge, along with a range of other factors. Those other factors are separated schematically by showing two different lines for GDP: one the result of knowledge, the other the result of all factors (knowledge plus other factors).

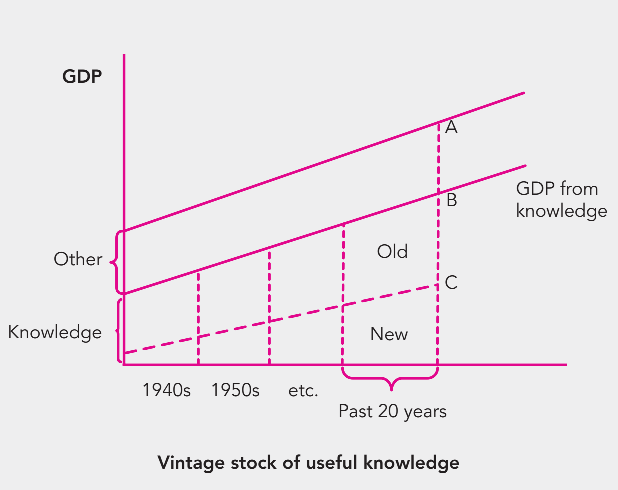
2 See, for example, Mokyr (2012), Jacobs (2014) and McCloskey (2011). Warsh (2006) sets out the complicated development of the economic understanding of the role of knowledge in the economy.

The stock of knowledge has a 'vintage' aspect to it: at any given time, GDP will depend on new or advanced knowledge as well as 'old' knowledge. It is expected that the share of new knowledge increases over time, but that increase is not necessarily linear.

Because GDP depends on the stock of knowledge and a range of other factors, it is not fully explained by knowledge over any timeframe.

Knowledge, in the sense used here, may be embodied in capital goods, processes or people.

Figure 1.1 Broad concepts: GDP and growing knowledge



Source: The CIE.

In Figure 1.1:

- Total GDP (at point A, for example) depends on new knowledge, old knowledge and a range of other factors. This can be represented as: GDP (*new knowledge, old knowledge, other factors*) = **A**.
- In principle, part of GDP is determined by knowledge alone; that is, GDP (*new, old*) = **B**.
- Also in principle, part of GDP is determined by new knowledge alone; that is, GDP (*new*) = **C**.
- The 'old' knowledge is the stock of previously produced knowledge that remains useful (for example, the quantity BC in the chart). 'New' knowledge could be knowledge from the past 20 years.
- C is a measure of the contribution of new knowledge to current GDP; equivalently, it is the potential loss in GDP should that knowledge be lost.
- Equivalently, C/A is the size of the sector of the economy that is based on new knowledge, expressed as a share of the economy as a whole.

From C (the part of GDP that depends on new knowledge), this study attempted to identify C_{SCI} (the part of the GDP that depends on *APM scientific knowledge*) and calculate C_{SCI}/A, which is the *share* of total economic activity that depends on this new scientific knowledge.

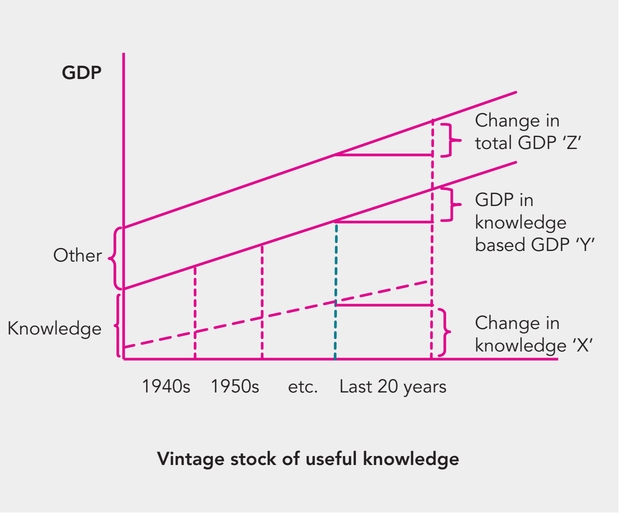
Our analysis follows from other studies that have attempted to make a similar calculation in other economies. The methods used to generate an estimate of C_{SCI} in those other studies vary, but they essentially involve identifying particular sectors with a branch of science and then adding up the economic contribution of that sector. This method and the results of those studies are discussed in the literature review in Chapter 4.

Difficulty in understanding marginal impacts

The analysis in this report does not directly measure marginal increments or the slope of the relationship between the stock of knowledge and GDP. This marginal relationship is illustrated in Figure 1.2. A change in knowledge of amount **X** may result in an increase in knowledge-based GDP of **Y** and a subsequent increase in total GDP of **Z**. This relationship (from **X** to **Y** to **Z**) is extremely hard to measure and requires controlling for a wide variety of variables. There is no generally agreed statistical relationship between knowledge (measured, for example as R&D) and GDP (or even components of GDP growth, such as productivity).

For example, as discussed in Chapter 4, the Productivity Commission failed to find a significant statistical relationship between R&D and productivity despite a very large econometric study (PC 2006a). There are many reasons for this. The commission noted that productivity and R&D are subject to different external drivers, and the existence of those drivers could obscure the relationship that it was trying to observe. External drivers that might affect one variable more than the other include policy and tax changes to R&D and economic policy reform that affects productivity.

Figure 1.2 The marginal impact of knowledge on GDP



Source: The CIE.

In order to provide insights into the importance of the APM sciences to the economy, the analysis in this report focuses on a 'bottom up' snapshot (looking at all sectors of the economy) of the current importance of those sciences; it does not attempt to look at the relationship between increases in APM scientific knowledge and increases in economic activity.

CHAPTER 2

2. HOW THE ADVANCED PHYSICAL AND MATHEMATICAL SCIENCES (APM SCIENCES) AFFECT THE AUSTRALIAN ECONOMY

The APM sciences can affect the economy in two broad ways.

First, they are the source of useful knowledge that is embodied in economic inputs (labour, capital and systems) that businesses use to produce output. In this way, they have a direct impact and flow-on impacts on the economy. The goal of this project was to identify the industries that use the APM sciences in this way and to quantify the total (direct and flow-on) economic impact of those sciences.

Second, APM scientific skills are dispersed throughout the economy and are useful to businesses in many industries that are not necessarily based on science. In effect, training in the APM sciences may increase the usefulness of workers in a variety of activities even if they are not directly involved in those sciences. While this effect is important, it is difficult to measure and is not quantified in this report

THE APM SCIENCES AS THE SOURCE OF USEFUL KNOWLEDGE

There is no single 'industry' that produces all science-based output. Rather, useful APM scientific knowledge affects a wide variety of industries and activities in the economy, as companies and other organisations use a range of inputs (labour, capital, materials and systems) that *embody* APM scientific knowledge in order to produce output. The size of the 'APM sciences based' sector in economic terms is the total value added, across all firms, that is produced from inputs that embody useful scientific knowledge.

As the source of useful knowledge that is embodied in economic inputs, the APM sciences have both a direct impact and a flow-on impact on the economy.

Direct impact

The direct impact is the extent to which the output (or value added) of a particular industry is higher than it otherwise would be as a consequence of the use of the APM sciences in that industry.

In broad terms, APM scientific knowledge makes an industry more productive than it would otherwise be; it can produce more (using the same inputs) than it could without the APM sciences. The case studies in this report give many such examples of this phenomenon.

To quantify the direct impact, we measured the amount of economic output that depends on inputs associated with the APM sciences. In particular, we focused on value added, as it can be summed across industries without double counting.

After adding that output for all the industries using the APM sciences, we refer to that measure as the 'size of the APM sciences based sector'. It is the magnitude of economic activity that has been 'allowed' or 'created' by the APM sciences. Similarly, the output produced using economic inputs that embody APM sciences, summed across all industries, is the 'APM sciences based output'.

APM sciences based output is produced by a variety of industries within the economy. Part of our research task was to identify those industries.

Flow-on impact

The increase in economic activity from the *direct* use of APM sciences within particular industries also has *flow-on* (or *indirect*) implications for all other industries in the economy (whether they use the APM sciences or not), as well as for consumers.

The flow-on effects arise because all activities in the economy are interconnected through a range of complex buying and selling relationships: the output of one industry is sold as an input to other industries, the output of which is then sold to other industries, and so on. Something that affects the first industry in this production chain will also affect other industries, and consumers, further along the chain.

In the case of APM sciences based industries, there are three flow-on mechanisms of particular interest:

- First, the change in output from activities directly using the APM sciences flows through to other activities in the form of better or cheaper products and services. Buying industries are then able to increase their output because of those improved products or services. In turn, they are able to pass on benefits to yet other industries, and so on. Ultimately, all businesses benefit from the direct and indirect use of products and services that originated from the use of the APM sciences.

  One of the main ways that this set of flow-on benefits is transmitted is through prices. The use of the APM sciences allows some products and services to be cheaper than they would otherwise be (telecommunications products are an example), and the price reduction benefits all industries that use them.

- Second, consumers are able to buy more and cheaper products, either directly from APM sciences based industries or from industries that buy the output from industries directly using the APM sciences. By directly and indirectly using APM sciences based output in this way, consumers are able to do things more efficiently, which frees up income to spend on other consumption.
- Third, some of the industries that indirectly use APM sciences based output are export industries. Exporters benefit both directly and indirectly from the APM sciences, and their export revenue has further flow-on effects throughout the economy.

Telecommunications is a good example to illustrate the full impact of the APM sciences on the economy:

- The direct impact is the part of telecommunications output that is produced using inputs that embody useful knowledge translated from the APM sciences (for example, mobile phone and wireless internet services).
- By using telecommunications services based on the APM sciences, businesses and consumers are able to communicate more efficiently and effectively. This creates productivity gains for businesses and savings for consumers. Because the use of advanced telecommunications is widespread, the magnitude of this flow-on impact is large.

HOW THE APM SCIENCES CREATE USEFUL KNOWLEDGE

To understand the impact of the APM sciences on the Australian economy, we must understand two processes:

- how 'science' knowledge is used to create 'useful' knowledge
- how this useful knowledge is embodied in inputs (labour, capital and systems) that are then used to generate output.

Figure 2.1 shows how these processes work and who undertakes them.

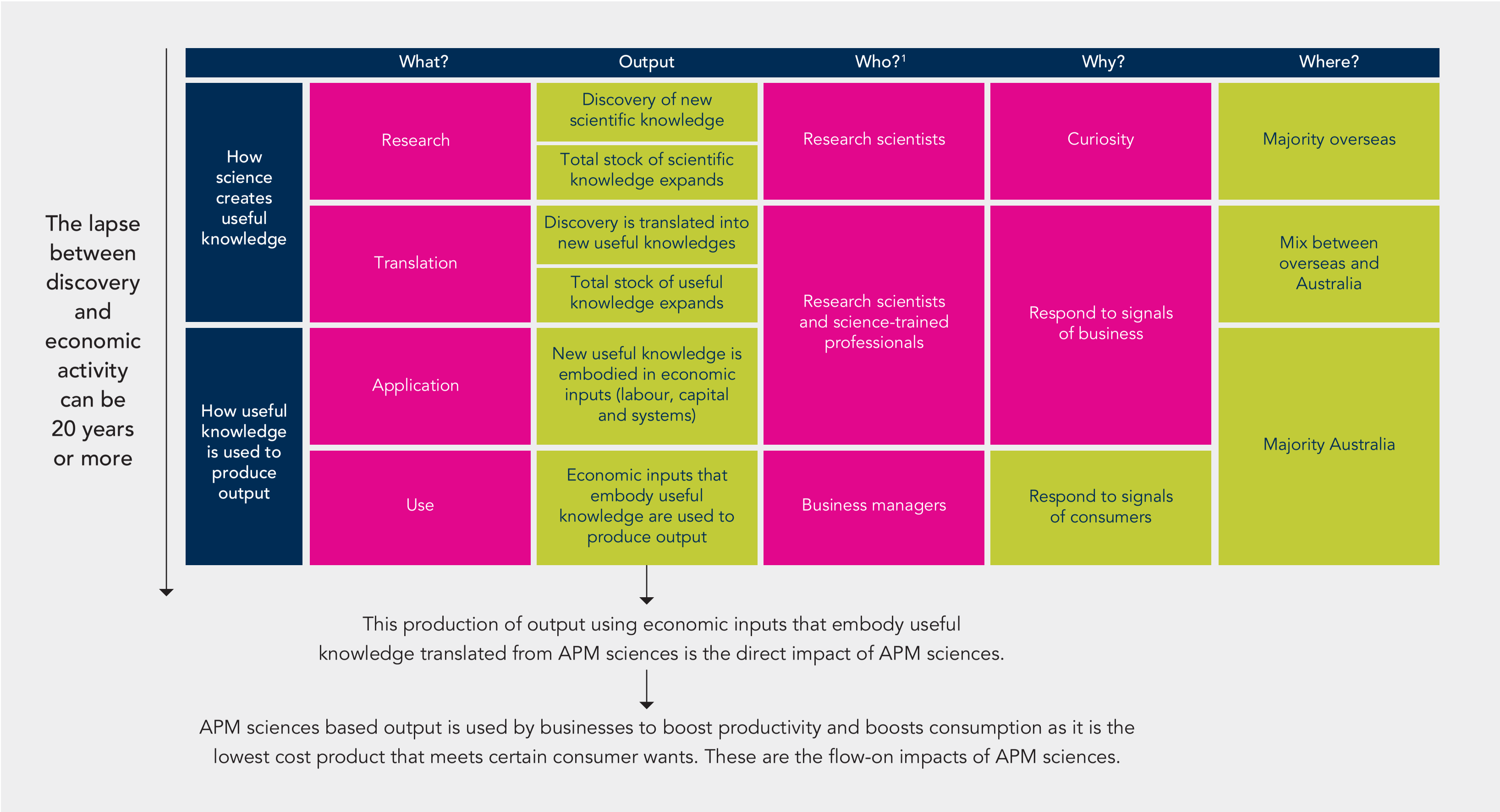
First, it is APM scientific research (driven by the curiosity of research scientists) that leads to the creation of new, advanced APM scientific knowledge.

Next, the new, advanced knowledge is translated into useful knowledge that can be applied. The useful knowledge is then incorporated into economic inputs (labour, capital and systems). These two steps are taken by APM research scientists and professionals trained in the APM sciences who respond to business signals.

Finally, business managers use the economic inputs to produce output. They act in response to consumer or export market signals.

Importantly, we should not consider research scientists, science-trained professionals and business managers as distinct groups. Science-trained professionals usually have strong links with research institutions and, in industries in which science is crucial, business managers can have science backgrounds. For example, many senior managers in the mining industry started as geologists.

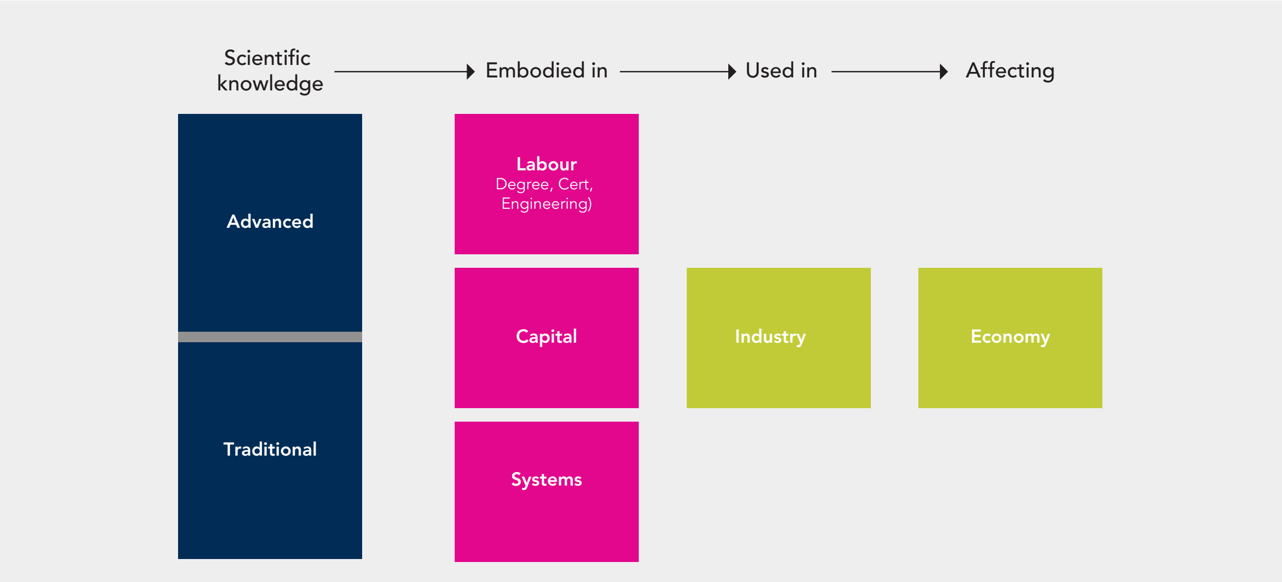
Figure 2.1 How science affects the economy



1 Research scientists, science-trained professionals and business managers should not be thought of as independent groups of people. Science-trained professionals can have strong links to research. Further, in sectors of the economy where science is crucial, business managers often have backgrounds in science. For example, many senior managers in mining companies started out as geologists.

Source: The CIE.

Figure 2.2 How science is embodied in different inputs



Data source: The CIE.

When useful knowledge is applied, it can be embodied in all economic inputs: labour, capital and systems (Figure 2.2).

The sources of useful knowledge within the APM sciences

Useful knowledge can arise from within the APM sciences in number of ways.

The first, and perhaps most obvious, is that the core disciplines of the APM sciences (mathematics, physics and chemistry) can provide useful knowledge individually. For example, chemistry provides useful knowledge that underpins the chemicals industry, and mathematics provides useful knowledge that is used by mathematicians in parts of the finance industry to run risk management and investment models.

However, the nature of science is multidisciplinary. Scientists are continuously combining principles from different disciplines to advance research and create more knowledge. Mixing principles between disciplines can be done in one of two ways.

- The principles of the core disciplines can be combined to form new 'non-core' disciplines, which are themselves independent fields of research and independent sources of useful knowledge. The earth sciences (which are treated as a single discipline in this study and are based on a combination of principles from the core disciplines) are an important non-core discipline for Australia, as they underpin exploration efforts that ultimately allow our mining industry to expand.
- The principles from the core disciplines can be combined directly to solve problems and create new useful knowledge. For example, in the late 1980s and early 1990s, the Australian scientists who invented the technology that became Wi-Fi did so by solving a physics problem with mathematics. To send data wirelessly using radio waves, they had to manage interference from different sources of radio waves (a physics problem); they did so by using a mathematical algorithm.

Overall, there are three sources of useful knowledge within the APM sciences: the core disciplines (independently of one another), the non-core disciplines (including the earth sciences, which are based on a combination of principles from the core disciplines), and direct combinations of knowledge from multiple disciplines.

This mixing of knowledge and principles across disciplines to create multidisciplinary knowledge means that the amount of useful knowledge that is translated from the APM sciences is *greater* than the amount that would be translated from the APM disciplines if they existed in isolation from one another.

As described above, 'science' knowledge has a direct impact (which arises from its embodiment in economic inputs that are used by some industries to produce output) and a flow-on impact (which arises from other industries and consumers using the science-based output).

Similarly, the multidisciplinary nature of science means that research work in individual disciplines can have a range of impacts. For example, an advance or innovation in mathematics could help mathematicians in banking to improve their risk and investment models *and* help physicists in telecommunications to improve Wi-Fi technology.

Chapter 5 describes the steps taken by the CIE to measure the importance of science to Australia, including a workshop for eminent Australian scientists and industry consultations. Both the scientists at the workshop and industry representatives emphasised the importance of the multidisciplinary nature of science. One industry representative noted that, in his view, it is the mixing of knowledge across disciplines that creates 'advanced' science.

Chapter 3 consists of a number of case studies that illustrate how economic inputs can embody APM scientific knowledge and the combination of principles and knowledge from different disciplines.

THE NATURE OF THE DIRECT IMPACT OF SCIENCE

The APM sciences have direct impacts on the economy in a number of ways, in addition to providing the useful knowledge that is embodied in economic inputs (Table 2.1). We did not measure the magnitude of all those direct impacts, because we focused only on the amount of output produced using inputs that embody APM scientific knowledge. As discussed in Chapter 9, this means that we have probably underestimated the true direct impact of APM sciences on the economy.

THE DIFFUSION OF APM SCIENTIFIC SKILLS THROUGHOUT THE ECONOMY

The second mechanism by which the APM sciences affect the economy is the diffusion of general APM scientific skills to parts of the economy that do not necessarily use science *per se*. This mechanism is not quantified in this report.

There are many people who undertake training in the APM sciences but who do not directly apply their scientific knowledge in their jobs (that is, they cannot be considered 'labour inputs' that embody APM scientific knowledge).

Table 2.1 The six ways that the APM sciences directly affect the economy

How science provides useful knowledge	Examples and discussion	Benefit captured in GVA?	Why?
1. New products/ processes that see activity increase	‣ Gravity gradiometry devices (case study 1) make mineral exploration more efficient ‣ Hunter Valley coal chain (case study 4) supports efficiency of supply chain	Yes	We can observe the increase in activity that results.
2. Asset development	Much science research is aimed at developing assets for future use.	Yes	We can observe the effect when new/ developed assets are used.
3. New products/devices that improve safety/health	Australia's tsunami warning system	No	Increased safety supports some activity, but this is difficult to observe.
4. Science that underpins regulation	Restrictions on manufacturing, transport etc.	No	Regulations may lead to decreases in measured activity.
5. New inventions associated with production improvements	Consumer pleasure and functionality increase with advances in computers and smartphones, facilitated by production improvements.	No	Production improvements contain price growth, so expenditure on products grows slowly compared with pleasure and functionality.
6. New products/ processes that save resources	3D imaging (Case study 6) optimises maintenance and replacement schedules for ore crushers in mining, and may save investment dollars.	No	If a new product saves resources, that could register as less economic activity. There is a need for company case studies to understand savings.

Source: The CIE

However, the problem-solving skills and critical thinking that they developed in their science training are still valuable to their employers.

The ANZSIC 2006 industry classification system used by the Australian Bureau of Statistics (ABS) splits the Australian economy into 506 industry classes. This study found that 158 (38%) of the industry classes are based on the APM sciences to some extent.

In the 2011 Census, the ABS divided the economy into 717 industry classes. Of those, 538 (75%) had at least one employee with a non-school qualification (NSQ) in the APM sciences.

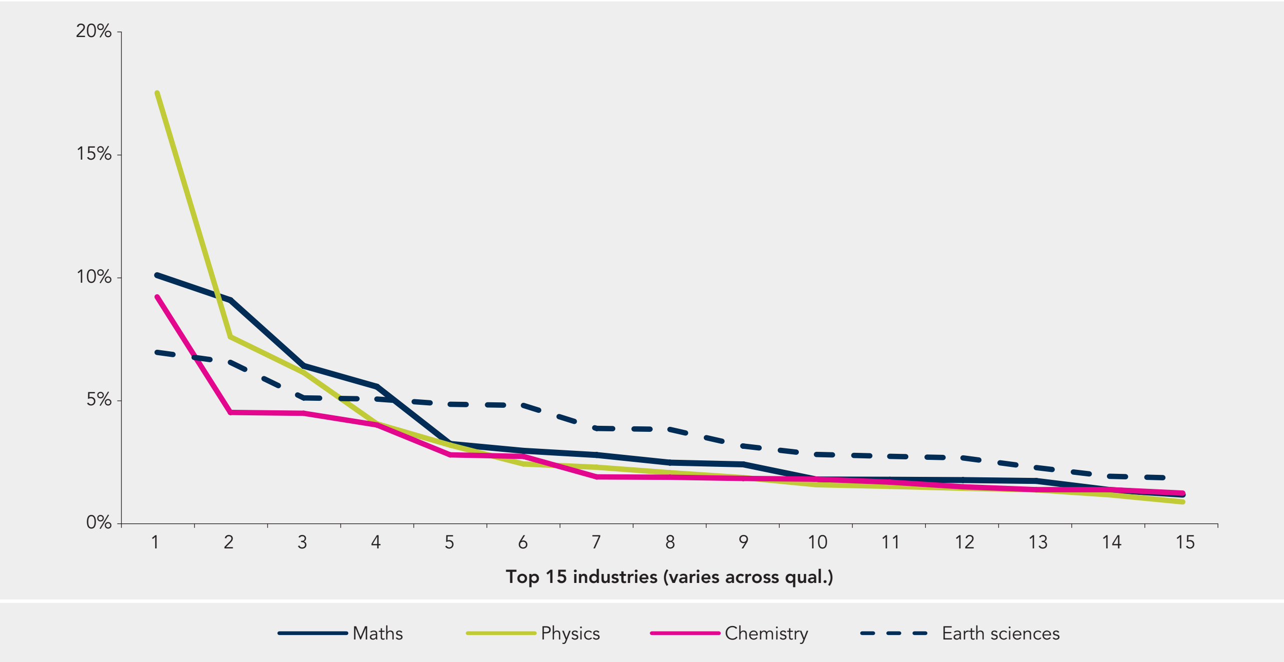
The contrast between these figures indicates that APM scientific skills are valuable to businesses in many parts of the economy, whether or not those businesses are strictly science-based and thus use such skills directly.

The spread of science across the economy is also illustrated by the fact that a very low percentage of people with qualifications in science work in the key APM sciences-based industries. Figure 2.3 shows total employment among individuals with an NSQ in a particular APM science, split by the industries that they work in (expressed as a share of the total); that is, it shows what proportion of all graduates in a particular discipline are employed in a particular industry.

From Figure 2.3, we can make the following statements:

- People with an NSQ in an APM science are spread right across the economy.
- *Higher education* (which includes universities) is a large employer of these individuals. It is the number 1 employer of people with an NSQ in maths, physics or chemistry, employing from 9% to 18% of them.

Figure 2.3 Proportion (%) of graduates with a non-school qualification in the APM sciences who are employed in particular industries



Industry destinations of individuals, by discipline

Discipline	1 (top employer of disc.)	2	10
Maths	Higher education (10.2%)	Computer sys. design (9.2%)	General insurance (1.8%)
Physics	Higher education (17.7%)	Computer sys. design (7.7%)	State gov. admin (1.6%)
Chem.	Higher education (9.3%)	Scientific res. serv. (4.6%)	State gov. admin (1.8%)
Earth sciences	Eng. des. & consult. (7.0%)	Mineral exploration (6.6%)	Scientific res. serv. (2.8%)

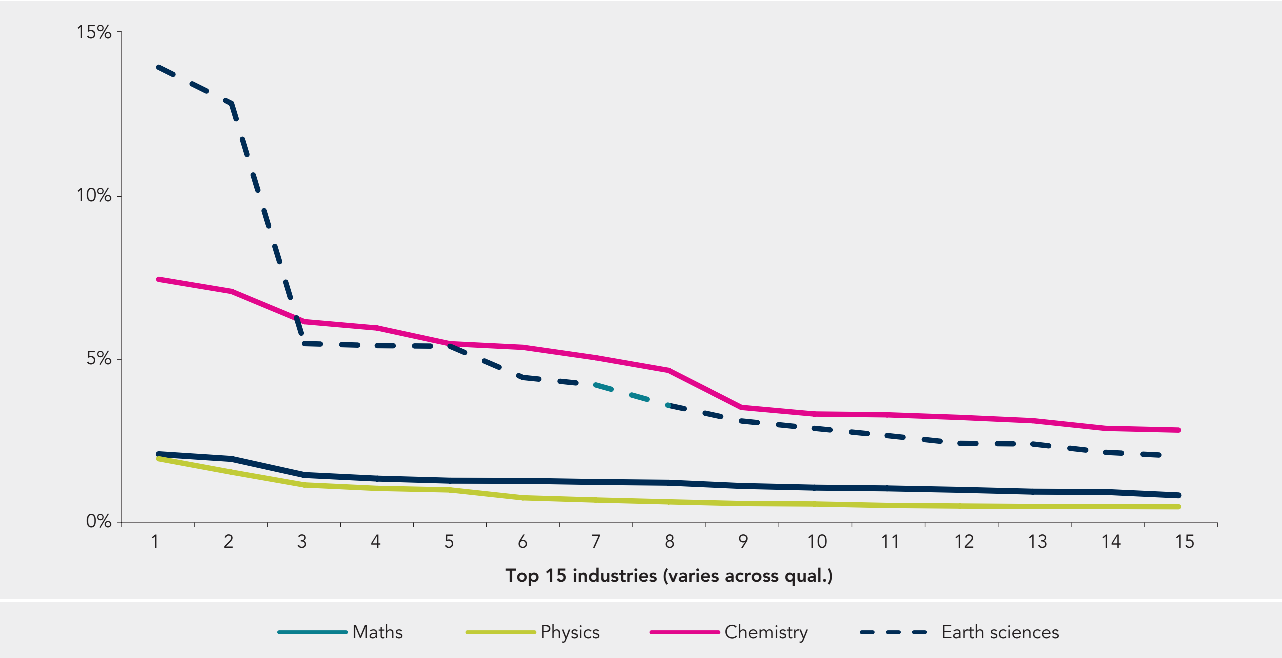
Data sources: ABS, 2011 Census; The CIE.

- *Engineering design and engineering consulting services* is the number 1 employer of people with an NSQ in earth sciences, employing 7% of them.

Because people with an NSQ in science are spread across the economy, they tend to make up only a small proportion of total employment in most industries. Figure 2.4 shows the proportion of all employees in a particular industry that have a qualification in a particular discipline:

- People with an NSQ in earth sciences make up 14% of employment in *petroleum exploration* (the number 1 industry for earth sciences graduates).
- People with an NSQ in chemistry make up between 5% and 10% of employment in some *chemical manufacturing* industries.

Figure 2.4 Proportion (%) of employment accounted for by qualifications in a particular discipline, by industry (%)



Industry destinations of individuals, by discipline

Discipline	1 (top employer of disc.)	2	10
Maths	Central banking (2.1%)	Market res. & stat. serv. (2.0%)	Hydro elec. generation (1.1%)
Physics	Scientific research serv. (2.0%)	Other prof. & tech. serv. (1.6%)	Comm. equip. man. (0.6%)
Chem.	Adhesive man. (7.5%)	Basic org. chem. manuf. (7.1%)	Vet. phar. & med. man. (3.3%)
Earth sciences	Petroleum exploration (14.0%)	Mineral exploration (12.8%)	Iron ore mining (2.9%)

Data sources: ABS, 2011 Census; The CIE.

CHAPTER 3

3. CASE STUDIES SHOWING THE IMPACT OF THE ADVANCED PHYSICAL AND MATHEMATICAL SCIENCES (APM SCIENCES)

This chapter provides five case studies that illustrate the points made in Chapter 2. Additional case studies appear in Chapters 6,7, 8 and 11.

Table 3.1 summarises all the case studies in this report and their relevance to particular APM sciences.

CASE STUDY 1: GRAVITY GRADIOMETRY

This case study illustrates how physics, geophysics and mathematics combine to improve the productivity of mineral exploration.[3] Modern mineral explorers need to look underground, and the measurement and analysis of gravity fields allow them to do so.

The technology: a combination of maths and physics

Physics, in particular geophysics, includes the study of the Earth's gravitational field. The strength of the field changes subtly from one point to another on the Earth's surface because the density of subsurface materials differs from place to place.

Gravity gradiometry devices take this principle from geophysics and use advanced sensors and modelling and data analysis techniques from mathematics to accurately measure and map changes in the Earth's gravitational field above ground. That information is then converted into a 3D map of changes in density below the Earth's surface. The changes in density can identify the presence and extent of valuable deposits of hydrocarbons and minerals.

The benefit

Exploring for deposits of hydrocarbons and minerals is time-consuming, expensive and difficult, and unsuccessful efforts are extremely costly. Gravity gradiometers reduce costs by improving the efficiency and effectiveness of exploration. They can be operated from aircraft, which means that geologists can use them to explore large areas for valuable deposits efficiently and accurately.

History of gravity gradiometry

Airborne gravity gradiometers were developed in the 1980s by Bell Aerospace (now owned by Lockheed Martin) and BHP Billiton (which at that time had research capability based in Australia) into instruments ready for aerial surveillance. They were first used in mining by BHP Billiton, which employed them to explore for diamond-bearing kimberlite pipes in 1999. Since then, they have been used successfully at a number of diamond mines, including the Ekati diamond mine in Canada and Abner pipe near the Finsch mine in Australia, as well as a number of iron ore, gold and copper bearing multi-mineral deposits. The Chilean Santo Domingo Sur copper deposit was discovered with the help of a gravity gradiometer.

Current research efforts

In recent years, there have been a number of efforts worldwide to develop gravity gradiometry technology further. Those efforts include the work of a team developing the VK1 gravity gradiometer at the University of Western Australia (UWA). The team's work is funded by Rio Tinto.

3 Sources for this case study: Hans Bachor (ANU) and CIE.

Table 3.1 Case studies in this report and their key points

Case study	Problem	Solution	Source of APM knowledge	Australian link and comments
1. Gravity gradiometry	Need for more efficient, effective mineral exploration	Capital that embodies science: gravity gradiometers operated from aircraft sense and map small changes in the Earth's gravitational field. This can indicate the presence of minerals.	A combination of physics (analysis of gravitational field) and maths (data analysis and mapping)	Team at University of Western Australia developing the VK1, which is a more accurate version of the technology.
2. Subsea pipelines	Test scale models to optimise design and minimise impact on the environment. Simulated mass of models must equal mass of pipelines.	Capital that embodies science: centrifuge spins models at high speed, increasing the gravitational force that acts on the models.	Physics	Uses world-leading centrifuges at the Centre for Offshore Foundation Systems in Western Australia.
3. Pipeline inspection gauges (PIGs)	Detect problems in pipes (corrosion and cracking) in timely fashion.	Capital that embodies science: PIGs are clever sensors that flow inside pipes with the travelling fluid and detect problems.	Physics (sensors) to pick up chemistry and physics problems	Example of how useful science knowledge cannot usually simply be imported (each pipeline is different).
4. Hunter Valley coal chain	Efficient management of the coal chain.	System that embodies science: coal chain management is governed by mathematical systems and models.	Maths	Developed by CSIRO and the University of Newcastle.
5. Horizontal. drilling	Accessing multiple oil and gas wells from one drilling rig.	Clever engineering (horizontal drilling) and earth sciences (precisely locate wells).	Earth sciences	--
6. 3D imaging	Precise detection of wear on surfaces of mining equipment.	Capital that embodies science: lasers create 3D map of surface, showing wear and tear.	Physics and maths	Technology invented in Australia.
7. Mobile broadband	Better communication networks.	Capital that embodies science: mobile broadband networks (2G, 3G and 4G technologies).	Physics and maths	Productivity benefits right across the economy due to innovation in science.
8. Wi-Fi	To send data wirelessly (using radio waves); must manage interference from different sources.	Manage interference using mathematical algorithm.	Physics problem solved with maths	Technology invented by Australians at CSIRO in the 1980s and 1990s.
9. Light-emitting diodes (LEDs)	LED crystal that emits blue light.	Research efforts to grow crystal.	Physic and chemistry	Science is an important source of new ideas that underpin long-run growth.

Source: The CIE.

The VK1, which has been 30 years in the making, is named after UWA physicist Dr Frank Van Kann, who invented many improvements of the technology. The VK1 measures changes in the Earth's gravitational field more precisely than earlier devices, which allows for the reconstruction of higher resolution maps of the location and the better identification of potential deposits. It makes mineral and hydrocarbon exploration efforts more efficient and effective.

Further improvements

The current generation of gravity gradiometers uses a mechanical balance system to measure changes in the Earth's gravitational field. The next generation will replace the balance with an atom interferometer (which can trace the properties and behaviour of individual atoms precisely). It will provide more accurate measurements of the location and nature of subsurface deposits in the same way that an atomic clock provides a more accurate measurement of the time than a mechanical clock. This will improve the accuracy of mineral exploration. Australian scientists at ANU are leading the race to make this advance. It is expected that this work will have very broad application throughout the economy.

CASE STUDY 2: SUBSEA PIPELINES

This case study illustrates how advanced physics can be used to improve the design of subsea infrastructure.[4]

Testing subsea infrastructure

Subsea infrastructure (including anchors and pipelines) used by the offshore oil and gas industry is subjected to large forces. If it is not designed to withstand those forces and fails, the costs are extremely high.

Anchors connect floating infrastructure (such as a platform) to the seabed via a link between the two. Anchors are subject to large forces when floating infrastructure moves with waves created by large storms.

Pipelines transport oil and gas from wells to surface infrastructure and onshore infrastructure. The forces acting on pipelines are large and complicated; they include forces arising from changes in temperature, seabed movement (which changes the supports of the pipeline) and the pipeline's own weight (when it spans two supports). In addition, the flow of oil and gas along a pipeline causes it to move laterally, subjecting it to large forces (in the same way that an ordinary garden hose that is turned on and left lying on the ground will thrash around).

Scientists at the Centre for Offshore Foundation Systems (COFS) at the UWA use robotic actuation to recreate such forces and apply them to scale models of subsea infrastructure. The performance of the models can be used to improve the final design of the anchors, pipelines and other pieces of infrastructure, reducing the probability that the infrastructure will fail.

The key problem

The impact created by some of the forces that act on the subsea infrastructure is a function of the weight of the infrastructure. This means that to be useful the scale models must behave as though they weigh as much as the infrastructure they represent.

The solution: use physics

The scientists at COFS solved this problem by placing the scale models in their world-leading centrifuges. The centrifuges spin the models at high speed, which increases the gravitational force that acts on the models so that they behave as though they weigh as much as the equipment that they represent. This work is based on the principles of physics.

The United States National Aeronautics and Space Administration also uses centrifuges to increase the gravitational force that acts on astronauts in order to test their reactions and tolerance.

CASE STUDY 3: PIGs AND PIPELINE MAINTENANCE

This case study illustrates the way in which advanced physics, using sensors to detect chemical and physical problems, can detect corrosion and cracking in pipelines.[5] This allows problems to be corrected before they lead to costly failures of pipeline infrastructure.

Australia has an extensive long-distance network of transmission pipelines. We have more than

4 Sources for this case study: Centre for Offshore Foundation Systems (COFS), Hans Bachor (ANU) and CIE.

5 Sources for this case study: Australian Petroleum Production & Exploration Association, *The Tech Drill* and CIE.

33 000 kilometres of high-pressure steel pipelines, of which more than 25 000 kilometres is used for natural gas transmission. Pipelines are usually buried, making them unobtrusive and quiet.

The problem: chemistry and physics

One of the challenges with long pipeline networks is in ensuring the integrity of the pipeline against corrosion or cracking, which is a set of problems in chemistry, materials science and physics. Given the decades of service expected from pipeline infrastructure, corrosion or cracking must be picked up early so that action is taken well before any risk of a pipeline failure occurs.

The solution: physics

One important tool used to verify pipeline integrity is an 'intelligent PIG'—a not very glamorous name for a high-tech industrial robot. PIG stands for 'pipeline inspection gauge' or 'pipeline intervention gadget'.

Intelligent PIGs are robot devices that are pumped through a pipeline to make detailed measurements of the pipeline's geometry, metal thickness, and cracks or corrosion in the pipe wall. They travel hundreds of kilometres through pipeline networks while the pipelines continue to work. The PIGs' environment can be very hostile. They face high pressures and are often in petroleum fluids. Only specially designed PIGs can work in these places.

The PIGs carry advanced physical sensors that allow them to make high-tech and specific measurements:

- They carry sensors to measure *magnetic flux*, or how easily induced magnetism flows through the metal (the healthier the pipe, the easier it is for magnetism to flow). The sensors can differentiate between internal and external corrosion and detect changes in nominal wall thickness.
- They use *ultrasonics* to measure wall thickness and cracks. The PIG can analyse the whole surface and length of the pipeline for traces of corrosion without any significant reduction in pipeline flow. Systems determine the extent, location, depth and internal or external position of corrosion.
- They are equipped with *callipers* to measure accurately the internal diameter of the pipe and pick up pitting in the wall.

The sensors acquire the necessary data using the principles of physics.

The PIG is an example of the mixing of knowledge across disciplines within the APM sciences to create new knowledge and solutions. Pipeline problems such as corrosion and cracking are problems in chemistry and physics, while the PIGS are based on physics.

Using PIGs at individual sites

At all pipeline sites and in all uses there are substantial differences in the types of problems encountered. From site to site, the design requirements and specifications, the use of PIGS and the interpretation of output data can also vary significantly.

This means that, in general, PIGs are a technology that cannot be applied 'off the shelf'. When they are used, there is usually a need for science-trained professionals to manage their use. Even when PIGs and associated technology are designed and built overseas, they cannot be usefully applied in Australia without input from Australians, or at least from people familiar with Australian conditions and projects.

This shows that there are limits to how much science Australia can 'import'. As a small advanced economy, Australia is a net importer of science. However, it is not possible for us to import all of the science that we benefit from. To be usefully applied in Australia, science knowledge needs to be developed and translated into knowledge that is useful for Australian conditions. PIGs technology is an example of this.

Locating problems

PIGs measure pipewall deformations using differential GPS surveying equipment. This locates anomalies (dents, buckles, wrinkles and bending strains) within an accuracy of 1:2000 from any known reference point. It also allows the assessment of the dynamics associated with slope instability, subsidence, overburden, frost heave, river crossings, free spanning, and temperature and pressure changes. Comparisons of repeat PIG survey data determine pipeline movements as small as 250 millimetres and differential bend curvature strain to +/− 0.02%.

These measurements are stored on board the PIG's computers for downloading at the end of its journey. With this information, a picture of the health of the pipe is acquired, and maintenance plans are updated to ensure that the pipeline stays in the best physical condition. The use of PIGs has resulted in significant savings (in the order of millions of dollars) for gas pipeline companies, which can avoid the cost of replacing valves unnecessarily.

CASE STUDY 4: THE HUNTER VALLEY COAL CHAIN

This case study illustrates the use of advanced mathematics (in particular, optimisation modelling) to address one of the most significant logistical challenges in the Australian economy.[6] The careful scheduling of coal trains through the Hunter Valley and on to the port substantially increases the efficiency of this key export industry.

The logistical challenge

The Hunter Valley Coal Chain Coordinator (HVCCC) is an independent body representing coal producers and coal industry service providers (the ship loading terminal, train operators, track owners and the port authority) in the Hunter Valley region of New South Wales. The coordinator is responsible for planning and scheduling the movement of coal through the supply chain from mine to ship. The operations that it covers include 35 coal mines run by 11 coal producers, 31 load points and 3 coal export loading terminals. It uses 44 trains and loads around 1400 vessels per year with around 140 million tonnes of coal (HVCCC 2012, Boland et al. 2013).

Moving so much coal through the supply chain is a considerable logistical challenge. The management of the system must take into account the flow and mixing of coal products, constraints on the loading facilities and tracks, including maintenance requirements, and the timing of vessels arriving in the port.

Optimising the supply chain

To the manage the supply chain optimally, HVCCC has worked with CSIRO and the University of Newcastle to develop a series of state-of-the-art models and simulation programs. The models use the latest developments in constrained optimisation. Optimisation algorithms are developed for various different applications in the supply chain.

Capacity planning

A capacity planning software library developed by CSIRO models all the operations and constraints of the supply chain. The models are able to identify bottlenecks in the chain. Based on the models and estimates of future throughput, demand plans for the system can be developed. The software is able to identify areas for expansion or investment that will provide the greatest increase in throughput for the minimum investment (CSIRO 2011). The models use state-of-the-art algorithms to determine these investments in the very complicated supply chain.

Rail scheduling

The rail scheduling system reduces the time spent by planners in drawing up the rail schedules, while at the same time minimising delays and train idle times and maximising throughput. The schedule needs to incorporate times for travel from the terminal to the mine, the loading of the coal, the journey to the dump station, maintenance, and refuelling. It also needs to coordinate the matching of trains, mines and dump stations, equipment for unloading, and the use of the tracks by other trains (including freight and passenger trains).

The daily rail schedule is formed by solving a complicated system of constrained optimisation problems. This is embedded in software developed for HVCCC by CSIRO (CSIRO 2011).

Slot management

Slot management, which was implemented in 2003, seeks to limit flow-on impacts from a disruption and thus minimise throughput losses. The process requires trains to run within allocated slots; if a train misses its slot, the management team uses the slot management system to find the best (the least disruptive) alternative.

Slot management has helped to reduce loss rates from 10% to 4% and to increase throughput by 4 million tonnes per year (with a market value of around $300 million) (RDAH 2014). This has been achieved through improvements to the management of existing infrastructure without any additional capital expenditure.

6 Sources for this case study: CIE and the references cited.

Performance improvements

The coal chain is responsible for $15 billion in export revenue (CSIRO 2012). With the use of the optimisation models, HVCCC has been able to continually increase the throughput of the supply chain. Throughput increased by 8% between 2007 and 2008 with the introduction of the management system (CSIRO 2012). As the models were improved, throughput continued to increase until 2013, when it reached 150.58 million tonnes, 12% higher than in 2012 (RDAH 2014). Increased annual throughput leads to additional export earnings.

In addition, vessel queues are better managed, loading and ship turnaround are faster, and demurrage costs are lower. The use of yard machines is optimised to minimise conflicts and maximise throughput, and stockpile layouts are optimised to make the most efficient use of stockpile space. The models can also help in managing and recovering from unplanned outages and unexpected breakdowns.

CASE STUDY 5: HORIZONTAL DRILLING

This case study shows how knowledge from the earth sciences, when combined with advanced engineering, allows greater and more efficient access to oil and gas resources, substantially increasing the productivity of the industry.[7]

Oil and gas wells

Oil and gas reserves are tapped with wells, which are made up of multiple strings of steel pipe, cemented in place. All elements are pressure-tested to ensure fluid isolation and to check the integrity of the subsurface system. In Australia, wells are typically 2000 to 4000 metres deep, although wells up to 5000 metres deep are fairly standard for the petroleum industry.

Drilling

Oil wells are created by drilling, using drilling rigs. The rigs hold kilometres of pipe beneath their drill floor and turn the pipe kilometres away. The drilling rig may have to be able to hold 400 tonnes of pipe while turning it with 1500-horsepower motors.

Directional drilling

Advanced engineering has created directional drilling, which allows for the creation of non-vertical wells. Horizontal wells, where required, have been routine in the oil and gas industry since the late 1980s and early 1990s (the first horizontal well in Australia was drilled in 1993 in the Cooper Basin).

To drill horizontally, engineers operate the drill so that more material is removed from one side of the drill than from the other, which means the well turns a corner, allowing precise directional control. In Australia, for example, it is not unusual for a directional well to reach 3000 or more metres horizontally.

Benefits of directional drilling

Directional drilling allows multiple oil and gas deposits to be tapped from a single oil and gas platform, which improves the productivity of the platform. The greater productivity is achieved by advanced earth sciences and exploration, which are needed to precisely locate multiple oil and gas deposits that are near one another.

The improved productivity of oil and gas rigs lowers the financial costs and environmental impacts of oil and gas extraction.

7 Sources for this case study: Australian Petroleum Production & Exploration Association, Hans Bachor (ANU) and CIE.

CHAPTER 4

4. LESSONS FROM RECENT LITERATURE

The impact of science and scientific R&D on a particular economy can be considered in one of two ways:

- First, by attempting to measure the marginal impact of knowledge on productivity and growth. Generally, this relationship has proved difficult to measure, as illustrated in an Australian study discussed below.
- Second, by providing a snapshot of the size of the APM sciences based economy. This has been done in a number of international studies looking at a range of disciplines. This chapter explains the results of those studies and the lessons that can be learned from them.

THE MARGINAL IMPACT OF KNOWLEDGE ON PRODUCTIVITY AND GROWTH

In the Australian context, the Productivity Commission undertook a comprehensive study seeking to establish the relationship between business R&D and Australian productivity (PC 2006a). The expected relationship is based on the idea that R&D creates 'knowledge assets' that generate a flow of services into production, and thus affects the productivity of Australian workers.

The report on the study documented various attempts to quantify the relationship between the stock of knowledge and the level of productivity, and between growth in knowledge and growth in productivity. However, the commission found that this work did not yield evidence of a strong, positive effect of business R&D on productivity. The commission posited that it was unable to observe this relationship in the economic data because both productivity and R&D had been subject to different external changes in recent years, and it was likely that those changes had either obscured or disrupted the relationship between them. Changes that might have affected one variable more than the other included policy and tax changes to R&D and economic policy reform that affected productivity.

MEASURING THE SIZE OF THE APM SCIENCES BASED SECTOR OF THE ECONOMY

Given the difficulties in quantifying the relationship between research and the economic value that it creates, a group of more recent studies has tried a different, somewhat simpler approach. Those studies have identified the APM sciences based sector of the economy and estimated its contribution, measured by its share of GDP and employment. Such studies have been undertaken for the United Kingdom, Italy, the Netherlands and the European Union. Typically, the relevant scientific institute (for example, the United Kingdom's Institute of Physics) has commissioned the study. The methodology developed for this report has incorporated lessons learned from the methodologies used in those studies.

The analytical framework of the international studies

In each case, the study considered a single science discipline (physics, chemistry or the mathematical sciences). In most cases, the authors of the study reports followed five steps:[8]

- They divided the economy into its constituent industries to a high level of detail.
- In conjunction with the relevant scientific institute and other stakeholders, the authors identified which of the

8 For Deloitte's studies of the contribution of mathematical sciences to the economy (2014b and 2012e), mathematical science occupations were first identified through stakeholder discussions and literature reviews; employment in those occupations was allocated across sectors.

constituent industries were 'based' on the particular science being considered. In general, to make this decision, they identified an industry as being based on the relevant science if the science was deemed to be 'critical' to the existence of the industry (that is, in a hypothetical case in which the science did not exist, the industry would not exist either).

- The authors calculated the 'direct' contribution of the particular science. This is the size of the sector, measured in two ways: first, the activity (GDP) that occurs in it; second, the employment attributable to it.
- They then calculated the 'flow-on' contribution of the industries based on the particular science, which is the activity and employment that occur in the industries that supply the sector and its suppliers with production inputs. In all cases, the flow-on contribution was calculated with multipliers derived from input–output tables.
- The authors also calculated the 'induced' contribution of the science-based sector, which is the household expenditure that flows from the direct and flow-on employment caused by the sector.

The total contribution of the APM sciences based sector is the sum of the direct, flow-on and induced effects of the sector.

Summary of results: the size of the APM sciences based sector in other economies

Table 4.1 shows the key results of the studies that, for a number of different economies, identified the sector based on a particular scientific discipline and calculated its contribution to the economy.

Across different economies and different scientific disciplines, the direct contribution of the particular science ranged from 3% to 16% of GDP and from 3.4% to 11% of employment. Similarly, the total impact of the science (including the flow-on and induced impacts) ranged from 10.1% to 40% of GDP and from 5.6% to 34.6% of employment.

Table 4.1 The size of the APM sciences based economy, according to different studies

		Contribution to GDP		Employment	
		Direct	Total	Direct	Total
		%	%	%	%
Physics sectors					
Deloitte (2012a)	United Kingdom	8.5	24.6	4.0	14.2
Deloitte (2012a)	England	8.2	26.4	3.9	15.4
Deloitte (2013)	Wales	9.7	13.9	3.7	6.0
Deloitte (2012b)	Scotland	9.8	14.5	4.6	7.8
Deloitte (2012c)	Northern Ireland	8.8	11.7	3.8	5.6
Deloitte (2012d)	Republic of Ireland	5.9	10.1	4.5	10.7
CEBR (2007)	United Kingdom	6.4	12.5	5.4	14.0
Deloitte (2014a)	Italy	7.4	21.4	6.1	32.4
CEBR (2013)	Europe	10.9	27.1	7.7	21.0
Chemistry sectors					
Oxford Economics (2010)	United Kingdom	3.0	21.0	3.4	25.8
Mathematical Sciences sectors					
Deloitte (2012e)	United Kingdom	16.0	40.0	10.0	34.6
Deloitte (2014b)	Netherlands	9.5	30.0	11.0	17.1

Source: Studies as cited.

LESSONS FROM INTERNATIONAL STUDIES

The international studies that have attempted to measure the importance of particular sciences in other economies have broadly followed the same methodology. By carefully considering this methodology, the CIE has identified a number of limitations in it. Those limitations mean that there are limits on how the results can be interpreted.

The limitations are listed and described here. The following chapter, which describes and evaluates the CIE's methodology, describes how we have dealt with the limitations in designing our own methodology.

The international studies did not consider multiple science disciplines at once

Because science is multidisciplinary, knowledge and principles from different disciplines are often combined to form new, useful knowledge that underpins economic activity. This was one of the key findings from our discussions with scientists and industry groups.

When measuring the importance of science to the economy, it is important to consider multiple disciplines simultaneously for two reasons:

- First, they must be considered simultaneously to get some understanding of how they combine to underpin different types of economic activity. This is necessary to get a complete picture of how science affects the economy.
- Second, the fact that different disciplines can be combined to create new knowledge means that there is considerable overlap in the parts of the economy that each single discipline affects. When only a single discipline is considered, this point may be missed.

For example, in Deloitte's report on physics in the Italian economy (Deloitte 2014a), the authors deemed the *electricity distribution* industry to be 100% based on physics. In our study (based on workshops and consultations), we have deemed *electricity distribution's* science-based component to be 30% of total activity, and have split that component into mathematics (80%) and physics (20%).

The key implication of missing the overlap between disciplines is that the results of studies that consider a single discipline are not additive with one another. For example, if a study were to consider the size of the mathematics-based sector in Italy, it is likely that the authors would allocate at least some of *electricity distribution* to mathematics. If they were to do so, and the size of their mathematics-based sector were added to Deloitte's physics-based sector, at least part of *electricity distribution* would be double counted.

In some cases, the international studies did not determine the dependence of some industries on science carefully

In Deloitte's report on physics in the Italian economy (Deloitte 2014a), for most industries, the authors essentially made a binary (yes/no) choice about whether the industry was 100% physics-based. As a result, 58 of 78 industries that were deemed to be physics-based were further deemed to be 100% dependent on physics.

The result of this approach is that the authors probably overestimated the size of the physics-based sector. For example, they deemed the *other professional, scientific and technical activities nec* industry to be 100% based on physics. It seems likely that some of the science that underpins this sector would be based on disciplines other than physics, and that some of the sector would not be based on advanced science in any way.

To deal with this problem in our own study, we followed a three-step process to estimate the dependence of each industry class on science.

- The CIE and the Academy hosted a workshop for eminent Australian scientists, who considered and debated all 506 industry classes in the ANZSIC 2006 classification system individually and provided estimates of their dependence on science.
- For industry classes important to the APM sciences based sector, we ran follow-up consultations with industry representatives to ensure that their industry experience matched the views from the workshop.
- After applying our own judgement to finalise the list, we discussed the overall result and our methodology with other economics experts.

In the workshop and consultations, we emphasised to participants the need to be realistic about the extent of science-based dependence.

Estimation of flow-on impacts in the international studies

The flow-on impacts of a sector arise from its interaction with other sectors in the economy. The studies summarised in Table 4.1 used multipliers derived from input–output tables to estimate flow-on impacts.

While economists accept the idea that sectors of the economy have flow-on impacts, most do not accept that multipliers derived from input–output tables yield a correct measurement of those impacts. The Productivity Commission recently published a review of the use and misuse of input–output multipliers (PC 2013). Similarly, the Australian Bureau of Statistics has expressed strong reservations about the use of multipliers (ABS 2013) and no longer publishes them.

Multipliers derived from input–output tables frequently *overstate* flow-on impacts because they do not take into account subsequent resource constraints as an industry expands and do not take into account a range of price effects that may mediate the initial impact of changes in the science-based sector.

As a general example, consider a case in which the APM sciences based sector and its suppliers purchase *Y* goods and services from other sectors. Input–output multipliers simply report that the flow-on impact of the APM sciences based sector is *Y*. However, if one were to remove the sector (and thus the demand that flows from it) from the economy, the suppliers of *Y* would drop their prices in response to the fall in demand. In turn, the fall in prices would prompt the businesses that remain (those that are not based on science) to move in and soak up some of *Y*.

Not all of *Y* would disappear if the APM sciences based sector were removed from the economy, which means that the marginal impact of the existence of the sector is smaller than *Y* (the flow-on impact that is implied by input–output multipliers).

It is preferable to use a well-specified economic model, such as a computable general equilibrium (CGE) or economy-wide model, to estimate the magnitude of an industry's flow-on impacts. This is because, in a CGE model, the response of the economy to a simulated change in key variables is governed by the change in prices caused by that simulated change. For this study, the CIE used its own CGE model to estimate the magnitude of flow-on and total impacts.

OTHER STUDIES

A study by Rothwell (2013) looked at the jobs in the United States that require high-level knowledge in a STEM (science, technology, engineering and mathematics) field. By identifying STEM occupations, the study inferred the importance of STEM knowledge to the US economy and highlighted the fact that STEM workers have both bachelor and higher qualifications and sub-bachelor level training.

Rothwell used a national qualification/occupation database to identify occupations requiring STEM knowledge, and then used census data along with the occupation data to infer the number of workers requiring such knowledge.

He found that around 20% of jobs in the United States required a high level of knowledge in at least one STEM field. Such jobs were in every sector of the economy, but were particularly prevalent in utilities, professional services, construction, mining and manufacturing.

PricewaterhouseCoopers has estimated that 'data-driven innovation added an estimated $67 billion in new value to the Australian economy, or 4.4% of GDP' (PwC 2014). Rather than measuring the knowledge embodied in jobs and technology in the economy, that study attempted to measure the impact of innovation (assumed to be driven by improved data) on labour productivity. Science knowledge could similarly be thought of as a means to improve productivity. Data are analysed as a tool in various sectors of the economy to enhance existing activities. Improvements in IT systems and accessibility enable the collection, analysis and use of complex datasets. Importantly, the PricewaterhouseCoopers report highlights the fact that data *per se* are not valuable, but rather that the use and application of the data create value. Science knowledge can be thought of in the same way—the knowledge itself is not valuable, but how the knowledge is applied enables value to be realised.

Other studies have sought to illustrate the value of science by showcasing the ability of scientists to help tackle important problems in our society. For example, the American Geosciences Institute has noted the importance of geoscience in ensuring reliable energy supplies, providing sufficient water supplies and sustaining the Earth's resources, among other things (AGI 2012).

Similarly, the Milken Institute (2009) has noted that there will be substantial savings for the US economy and for businesses from reducing the high incidence of chronic disease in the United States, and the role that the life sciences can play in this.

WHAT DO WE TAKE FROM THE LITERATURE?

The CIE used the lessons identified in the methodologies of other studies to develop and enhance the methodology for this study. This is explained in Chapter 5 and discussed further in Chapter 9.

CHAPTER 5

5. THE METHODOLOGY USED IN THIS ANALYSIS

In Chapter 2, the direct and flow-on impacts of the APM sciences on the Australian economy are defined and explained. This chapter explains the practical steps taken by the CIE to measure those impacts.

In this study, the magnitudes of the direct impact and the flow-on impact are expressed as shares of gross value added (GVA) in the economy. GVA is also defined and explained in this chapter.

MEASURING THE DIRECT IMPACT OF THE APM SCIENCES

There is no single 'APM sciences' sector for which separate statistics measuring the value of economic activity are collected. (This contrasts with the agriculture and manufacturing sectors, for example, for which value added statistics are readily available in the national accounts.) Consequently, the value of the economic activity that is attributable to the APM sciences must be inferred indirectly.

The direct impact of the APM sciences arises from the fact that they are a source of useful knowledge that is embodied in economic inputs (labour, capital and systems) that are used by businesses to produce output. To measure the magnitude of this direct impact, we need to measure the share of economic activity that is produced from economic inputs that embody useful knowledge translated from the APM sciences.

Across the economy, total output is the sum of economic activity across industries. To estimate the total (economy-wide) output that is based on APM sciences, we estimated the quantity of economic activity in each industry component that is based on the APM sciences and then summed across industries.

Splitting the Australian economy into its component industries

The Australian Bureau of Statistics (ABS) divides the Australian economy into industries, sub-industries and so on using the ANZSIC 2006 industry classification system. In that system, the economy can be split into:

- 19 industries
- 86 sub-industries
- 214 industry groups
- 506 industry classes.

For this project, the CIE decided to split the Australian economy at the most detailed level—the 506 industry classes.

Measuring the quantity of activity that is based on the APM sciences in each industry class

The quantity of APM sciences based activity in each industry class is the total activity multiplied by the share of that activity that is based on the APM sciences. In most cases, that share is not 100%, as other factors (including science that is not 'advanced') also determine industry activity.

Gross value added in each industry class
To produce output, businesses in each industry combine intermediate inputs (outputs produced by other industries) and their own economic activity (their use of labour, capital and systems).

In each industry class, GVA measures the economic activity undertaken, as it is calculated as total output produced less intermediate inputs used. It is the 'extra' value added by each industry.

We estimated GVA in current prices for 2012–13 in all 506 industry classes. This involved the following steps:

- Data for economy-wide GVA and GVA in all 19 industries were taken from the ABS annual national accounts release (ABS Cat. 5204.0).
- For the manufacturing industry, GVA was allocated directly to constituent industry classes using industry value added data from the ABS Australian industry release (ABS Cat. 8155.0).
- For the non-manufacturing industries, GVA was allocated to industry groups using employment data from the ABS labour force release (ABS Cat. 6291.0.55.003) and then to industry classes using employment data from the 2011 Census.

The share of activity that is based on the APM sciences

For all 506 industry classes, we determined:

- whether any activity that occurs in the industry class uses inputs that embody useful knowledge from the APM sciences
- if yes, the share of total activity that uses inputs that embody useful knowledge from the APM sciences
- the APM sciences that the useful knowledge comes from.

To answer these questions, we applied five tests (listed in Table 5.1) to each industry class separately.

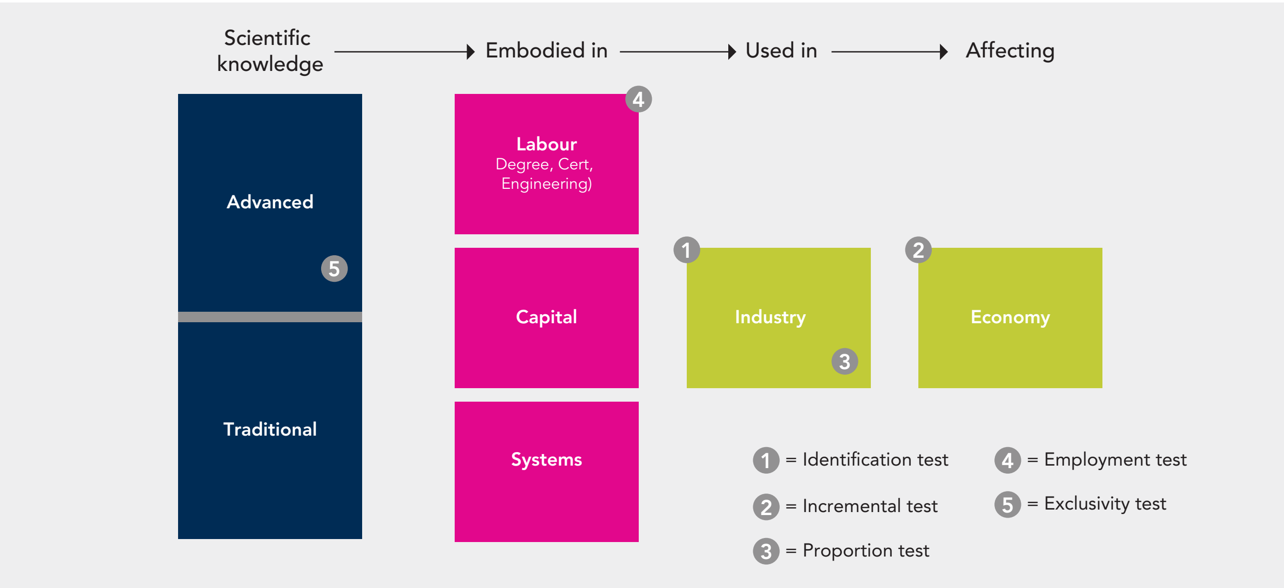
Figure 5.1 shows how these tests fit into the framework used to understand how scientific knowledge affects the economy.

Table 5.1 Five tests to determine the contribution of the APM sciences based sector to individual industry classes

Test	Question underpinning the test
1. Identification	Is the industry clearly science-based, or clearly not?
2. Employment	Does employment indicate that the industry relies on science?
3. Proportionality	If the industry is science-based, is it 100% science-based? If not, what proportion of activity in the industry is science-based?
4. Exclusivity	Of the science that underpins the industry, what proportion is mathematics, physics, chemistry and earth sciences? Or is it 'general science'?
5. Incremental	If scientific knowledge were removed, would that be catastrophic for the industry? If not, and if scientific knowledge were to revert by a significant amount, by how much would activity in the industry decline?

Source: The CIE.

Figure 5.1 The five tests and the impact of science on the economy



Data source: The CIE.

The five tests were applied to all 506 industry classes, and the results were checked, in a three-step process.

Step 1: A workshop for experienced Australian scientists
The Academy and the CIE hosted a workshop in Canberra over two days, attended by 13 Australian scientists chosen under the expert advice of the Academy's national committees for science. The scientists were chosen based on their wide experience and expertise, including in the application of APM sciences. They comprised an expert working group (members are listed in Appendix 3 of this report).

The scientists were split into two groups, and each group considered all 506 industry classes, systematically applying all five tests to each class. The results from both groups were compared and cross-checked, before being consolidated into a complete dataset. (As noted below, we used differences in outcomes and interpretations from the workshop as the basis for estimating the uncertainty of our results.)

Step 2: Industry consultations
From the consolidated dataset coming from the workshop, we identified key industry classes that were clearly important to the APM sciences based sector. They included the oil, gas and exploration industry classes, some mining industry classes, banking, health insurance, chemicals industry classes and telecommunications. Industry consultations were also undertaken for market research, food processing and aspects of the finance sector.

For each of the key industry classes, we put the same five tests to industry representatives or economic experts in follow-up consultations. This allowed us to check that the opinions of the workshop scientists matched the experience of industry and the opinions of others. In most cases, we found that to be the case. In a few industry classes, an adjustment was made to the share of activity that is based on the APM sciences.

Step 3: Further cross-checking
We applied our own judgement to finalise the list of industry classes based on the APM sciences, the quantity of activity that is based on those sciences and the disciplines that underpin that activity. We discussed the overall result and our methodology in broad terms with other economic experts.

The results of these three steps are presented in Chapter 6.

MEASURING THE FLOW-ON AND TOTAL IMPACTS OF THE APM SCIENCES

Unlike the direct impact of APM sciences, the total and flow-on impacts are not measured in economic statistics. Estimating flow-on effects requires a technique that can capture the relationships between industries in the economy and between industries and consumers. A common means of doing this is to use input–output tables. Input–output analysis by itself, however, is not sufficient to fully capture flow-on effects.

To measure the flow-on impact of the APM sciences, we used a computable general equilibrium (CGE) or economy-wide model of the Australian economy—the CIE-REGIONS model (a detailed description of the model is in Appendix 2 of this report).

Because economy-wide models capture the complex linkages between industries within the economy, they are ideal for measuring flow-on impacts. While they contain all the same information that is embodied in input–output tables, they do not rely on the restrictive assumptions of input–output analysis and are better able to capture the full range of flow-on impacts.

To estimate the total impacts (and from there the flow-on impacts) of the APM sciences, we used the model to simulate the direct impact of the sciences for each of the industries that use APM scientific inputs. In particular, we used the model to measure the productivity improvement in each industry that would lead to an increase in value added in that industry equivalent to the estimated *direct* impact of the APM sciences in that industry. These productivity improvements were then simulated in order to measure the total impact of the APM sciences. The use of a simulated productivity improvement captures the fact that the APM sciences based sector is able to produce more output from its starting inputs as a consequence of using the APM sciences. This approach is designed to simulate the way that scientific knowledge works.

The model simulations results allowed us to estimate the total impact, after all economic adjustments have taken place, of the initial direct impact. The total impact, minus the initial direct impact, is a measure of the net flow-on impact.

As explained in Chapter 6, in the Australian economy the APM sciences based sector is made up of activity across 158 industry classes. We mapped that activity into the 58 sectors in the CIE-REGIONS CGE model using standard mapping techniques. In this way, we identified the APM sciences based sector in the CGE model.

SOURCES OF UNCERTAINTY IN THIS METHODOLOGY

The CIE's estimates of the direct impact and the flow-on impact of the APM sciences are presented in Chapter 6 and Chapter 7.

For each of those impacts, we give an 'average' or 'middle' result. We also give 'high' and 'low' results (which create a range around the average result) because our results are subject to some uncertainty. The sources of that uncertainty are as follows.

Uncertainty associated with the direct impact of the APM sciences

The direct impact of the APM sciences is the sum of APM sciences based activity across all industry classes. It is not possible to estimate with precision the amount of that activity that occurs in each industry class. The estimates that we have derived are based on judgements by scientists and industry representatives in the workshop and consultations, which inevitably varied to some degree.

Our estimates of the 'high' and 'low' range for the direct impact of the APM sciences arise from our analysis of the uncertainty associated with the results gathered in the workshop and industry consultations.

Uncertainty associated with the flow-on impact of the APM sciences

Just as the direct impact of the APM sciences is subject to uncertainty, there is uncertainty associated with the flow-on impact. This uncertainty comes from two sources:

- uncertainty associated with the direct impact, which transfers into the flow-on impact
- uncertainty associated with economic modelling that is based on a number of underlying parameters, which are themselves uncertain.

EVALUATING OUR METHODOLOGY

As shown in Chapter 4, the CIE methodology described in this chapter is an improvement on the methodology used in other studies overseas. The improvements are discussed in Chapter 9, where our methodology and results are evaluated.

Chapter 9 also presents an evaluation of the expression of the impact of the APM sciences in terms of GVA.

THE BASIS OF THE IMPACT OF THE APM SCIENCES: TOTAL GVA IN THE ECONOMY

In this report, the direct, flow-on and total impacts of the APM sciences are reported as shares of total GVA in the economy. GVA is a measurement of economic activity by firms and government.

To measure total GVA in the economy, we excluded the GVA of the *ownership of dwellings* industry, because the GVA of that industry is imputed by the ABS (rather than observed via surveys, as it is for other industries).

This is consistent with the ABS's own methodology. In its *Year Book Australia* (Cat. 1301.0), the ABS illustrates the structure of the economy by calculating the GVA of each industry as a share of total GVA, where the total excludes the *ownership of dwellings* industry.

CHAPTER 6

6. THE DIRECT IMPACT OF THE ADVANCED PHYSICAL AND MATHEMATICAL SCIENCES (APM SCIENCES)

We measured the magnitude of the *direct* impact of the APM sciences by calculating the amount of output that is produced using economic inputs that embody useful knowledge translated from those sciences. This chapter reports our findings. The *indirect* impact is discussed in the next chapter.

THE SIZE OF THE APM SCIENCES BASED SECTOR

Following the workshop and industry consultations, 158 of 506 ANZSIC 2006 industry classes were deemed to be based on the APM sciences to some extent.

For an industry class, its GVA measures the amount of economic activity by firms in the class. For the 158 industry classes deemed to be based wholly or in part on the APM sciences, the value of total GVA was estimated to be $540 billion in 2012–13.

The workshop and industry consultations suggested that 26.8% of total activity in the 158 industry classes was based on science. That is, the size of the APM sciences based sector was 26.8% of $540 billion, or $145 billion, in 2012–13.

The sector made up 11.2% of the total value of GVA across all industries in 2012–13 ($1297 billion).[9]

We used the share of science in total GVA to represent the share of science in the total GDP of the Australian economy. GDP is the GVA of all industries plus net indirect taxes. For clarity, we excluded explicit analysis of indirect taxes. This is equivalent to assuming that the pattern of indirect taxes in the science-based sectors is similar to that in other sectors.

The finding from our analysis is that the APM sciences based sector directly makes up 11.2% of the Australian economy (Table 6.1).

As explained in Chapter 5, it is impossible to estimate precisely the share of activity in each industry class that is derived from inputs that embody useful knowledge derived from the APM sciences. Our analysis of that uncertainty has led us to conclude that the magnitude of the direct impact of the APM sciences probably lies in the range between 9.8% and 13.4% of the economy, as shown in Figure 6.1. In terms of GVA, the size of the APM sciences based sector lies in the range between $127 million and $174 million.

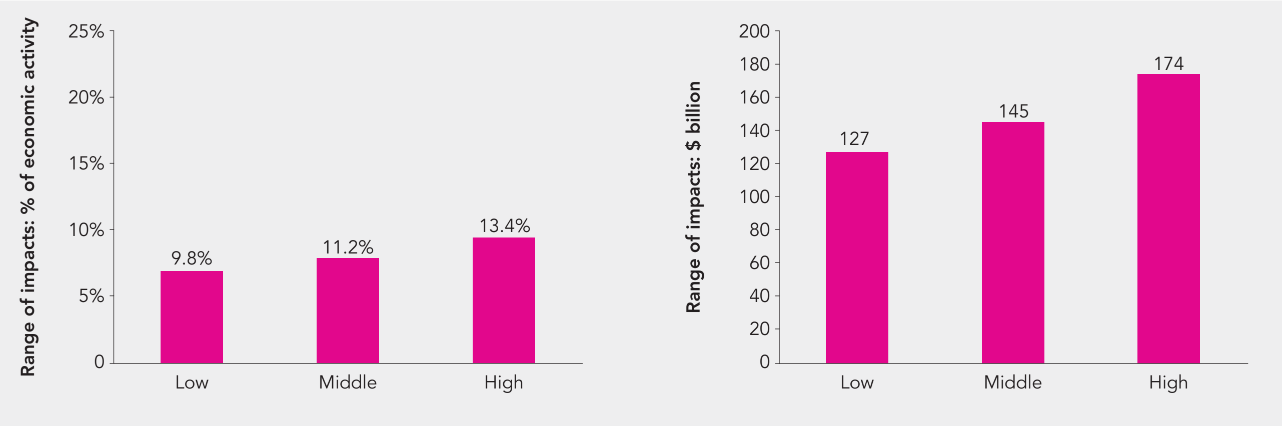
Table 6.1 Gross value added by sector, 2012–13

	Total ($ billion, current prices)	Science-based ($ billion, current prices)	Science share (%)
GVA of APM sciences based industry classes	540	145	26.8
GVA of non-science-based industry classes	756	0	
Total GVA	**1297**	**145**	**11.2**

Note: To express APM sciences based GVA as a share of total GVA, we excluded from the total the GVA of the *ownership of dwellings* industry, as it is imputed by the ABS and the industry does not employ any people (it makes up 9% of the total).

Sources: ABS; The CIE.

Figure 6.1 The direct impact of the APM sciences: range of estimates (% of economic activity, $ billion)



Note: To express APM sciences based GVA as a share of total GVA, we excluded from the total the GVA of the *ownership of dwellings* industry, as it is imputed by the ABS and the industry does not employ any people (it makes up 9% of the total).

Data source: The CIE.

INDUSTRY SUBSECTORS

Within the APM sciences based sector, the GVA of the top 10 industry classes was $67 billion in 2012–13 (or 46% of the GVA of the whole APM sciences based sector). The larger APM sciences based industry classes are in the mining sector (including *oil and gas extraction*, *iron ore mining* and *gold ore mining*), the finance sector (including *general insurance* and *banking*) and the communications sector (including *wired telecommunications network operations*). These components are shown in Table 6.2.

The largest single APM sciences based industry class was *oil and gas extraction*. In 2012–13, the GVA of the APM sciences based component of that class was $16 billion, which was 50% of total GVA for the class.

Table 6.2 Gross value added by the APM sciences based sector, by industry class, 2012–13

Industry classes		Total GVA ($ billion, current prices)	Science-based GVA ($ billion, current prices)	Science share (%)
700	Oil and Gas Extraction	32	16	50.0
6322	General Insurance	19	8	40.0
801	Iron Ore Mining	23	7	30.0
804	Gold Ore Mining	17	7	40.0
5801	Wired Telecommunications Network Operation	16	7	40.0
8520	Pathology and Diagnostic Imaging Services	5	5	100.0
6221	Banking	54	5	10.0
7000	Computer System Design and Related Services	24	5	20.0
5802	Other Telecommunications Network Operation	7	4	60.0
4610	Road Freight Transport	19	4	20.0
Total of other science-based industry classes		325	78	23.9
Total of science-based sector		540	145	26.8

Sources: ABS; The CIE.

Table 6.3 APM sciences based employment in the Australian economy, by sector, 2012–13

	Total ('000 people)	Science-based ('000 people)	Science share (%)
APM sciences based industry classes	3 425	763	22.3
Non-science-based industry classes	7 972	0	0.0
Australian economy	11 397	763	6.7

Sources: ABS; The CIE.

EMPLOYMENT

To estimate employment in the APM sciences based sector, the CIE followed the same process as for GVA. For each APM sciences based industry class, APM sciences based employment equals total employment in the industry class multiplied by the share of activity that is based on the APM sciences.

While the calculation for employment is the same as the calculation for GVA, the result is slightly different. This is because productivity (GVA per worker) in the APM sciences based industry classes is relatively high, which means that those industry classes require relatively fewer workers to produce output. For example (as described above), 50% of activity in the *oil and gas extraction* industry class is judged to be based on the APM sciences. In 2012–13, while GVA in *oil and gas extraction* ($32 billion) was 2.5% of GVA for all industries, employment in that class (24 000 people) was only 0.2% of total employment. This means that APM sciences based GVA in the *oil and gas extraction* industry class is equivalent to 1.25% of GVA for all industries, but employment based on the APM sciences in that class is equivalent to only 0.1% of total employment.

Overall, we estimated employment in the APM sciences based sector to be 763 000 people in 2012–13, or 6.7% of total employment (Table 6.3).

LABOUR PRODUCTIVITY

Productivity (GVA per worker) is high in the APM sciences based sector. This is because the industries that make up a large part of the sector (mining, finance and communications) use relatively large amounts of capital per worker to produce output and because those industries employ workers who are educated to a relatively high level.

We estimated that labour productivity in the sector was $190 000 per worker in 2012–13, which was 75% higher than productivity in other parts of the economy ($108 000; see Table 6.4).

Table 6.4 Gross value added, employment and productivity, by sector, 2012–13

	GVA ($ billion, current prices	Employment ('000 people)	Productivity ($'000 per worker)
APM sciences based sector	145	763	190
Non-science-based sector	1 153	10 634	108
Total	1 297	11 397	114

Sources: ABS; The CIE.

BUSINESSES

As noted, the ANZSIC industry classification system splits the Australian economy into 506 industry classes, of which 158 were deemed to be based on the APM sciences to some extent.

The ABS *Counts of Australian businesses* release (Cat. 8165.0) provides data on the number of businesses, by business size, for 496 industry classes. At June 2013, it reported that there were about 2 079 000 businesses in Australia.

Of the industry classes reported in *Counts of Australian businesses*, 157 are based on the APM sciences to some extent.[10] There were about 490 000 businesses in those business classes. Of those, 463 000 were relatively small (with a turnover of $2 million or less); 27 000 were larger (with a turnover of over $2 million).

CASE STUDY 6: 3D LASER IMAGING AND MINING

Three of the top four industry classes using the APM sciences are in mining. This case study illustrates how advanced physics and mathematics can be used to create 3D images to examine wear and tear in mining and milling equipment, making maintenance less expensive and allowing productivity increases in the industry.[11]

A maintenance problem

At mine sites, giant crushers and grinding mills smash rocks so that valuable minerals can be extracted. This equipment is subject to wear and requires maintenance and eventually replacement.

To schedule maintenance and replacement, the mine operator has to monitor wear on the wear surface of the mill (the surface that contacts the rocks). Monitoring is expensive, as production is lost when the machines are stopped and inspected. Before 3D laser imaging, personnel would enter the machines and measure wear at a few points on the wear surface of the mill.

However, suboptimal maintenance and replacement are even more costly. The equipment is expensive to maintain and replace, and the time involved means that the cost in lost production is large. Before 3D laser imaging, maintenance and replacement could be significantly suboptimal because of imprecision in measurements taken by personnel, errors and the fact that a few measurements cannot give a comprehensive picture of the state of the wear surface.

The scientific solution

Curtin University researchers invented MillMapper, which uses 3D laser imaging to improve this process. In a 15–30 minute inspection, this technology uses laser scanners to gather data from the entire visible part of the wear surface. Software then converts the data into a 3D map of the surface. The 3D aspect of the map is that the surface is colour coded to illustrate differences in thickness, to an accuracy of 3 millimetres. Because wear creates differences in thickness, the map allows the mine operator to monitor wear more accurately and comprehensively than was previously possible.

Because the MillMapper technology allows the mine operator to better monitor wear, the operator can make better decisions on the scheduling and nature of maintenance and replacement, substantially reducing costs.

Scanalyse (a company now owned by Outotec) was founded by the Curtin University researchers to own and sell MillMapper. Scanalyse won the 2013 Australian Museum Rio Tinto Eureka Prize for the commercialisation of innovation for MillMapper and the similar CrushMapper product.

10 ABS 8165.0 does not contain data on the *7711 Police services* industry class, which is the 158th industry class deemed to be based on the APM sciences.

11 Sources for this case study: Hans Bachor (ANU), Mining Australia, Outotech and CIE.

CHAPTER 7

7. THE FLOW-ON IMPACT OF THE ADVANCED PHYSICAL AND MATHEMATICAL SCIENCES (APM SCIENCES)

Chapter 5 describes how the CIE measured the flow-on impact of the APM sciences. This chapter presents the results of our model-based analysis of the impact.

THE MAGNITUDE OF THE FLOW-ON IMPACT

Simulations using the CIE-REGIONS model indicated that the flow-on impacts from the direct use of the APM sciences accounted for another 11.3% of Australian economic activity, on top of the 11.2% accounted for by direct impacts.

The total impact of the APM sciences in 2012–13 was therefore a 22.5% increase in economy-wide GVA.

Equivalently, the direct impact of the APM sciences was that the economy expanded by $145 billion, while the flow-on impact added a further $147 billion increase. In total, activity increased by $292 billion (Figure 7.1 shows all results).

The magnitude of the flow-on impact of the APM sciences on the economy, measured as a share of the economy, was between 7.5% of output and 15.9% of output. Overall, the total impact of the APM sciences on the economy was between 17.5% and 28.1%.

The magnitude of the flow-on impact, measured as GVA, was between $97 billion and $206 billion.

The total impact was therefore between $227 billion and $364 billion of GVA in 2012–13.

SOURCES OF INDIRECT IMPACTS

The indirect impact of the APM sciences arises from the use, by other industries and consumers, of outputs based on those sciences. In the CIE-REGIONS model (as in reality), the nature of outputs and target customers varies substantially across industries. As a result, the contribution to the flow-on effect from within the APM sciences based sector varies substantially among its component industries.

Industries that produce output that is used widely throughout the economy tend to create large flow-on effects. For example, the flow-on effect created by *communications* and *business services* (which includes various types of professional and technical services) is three times the size of the direct effect associated with those industries.

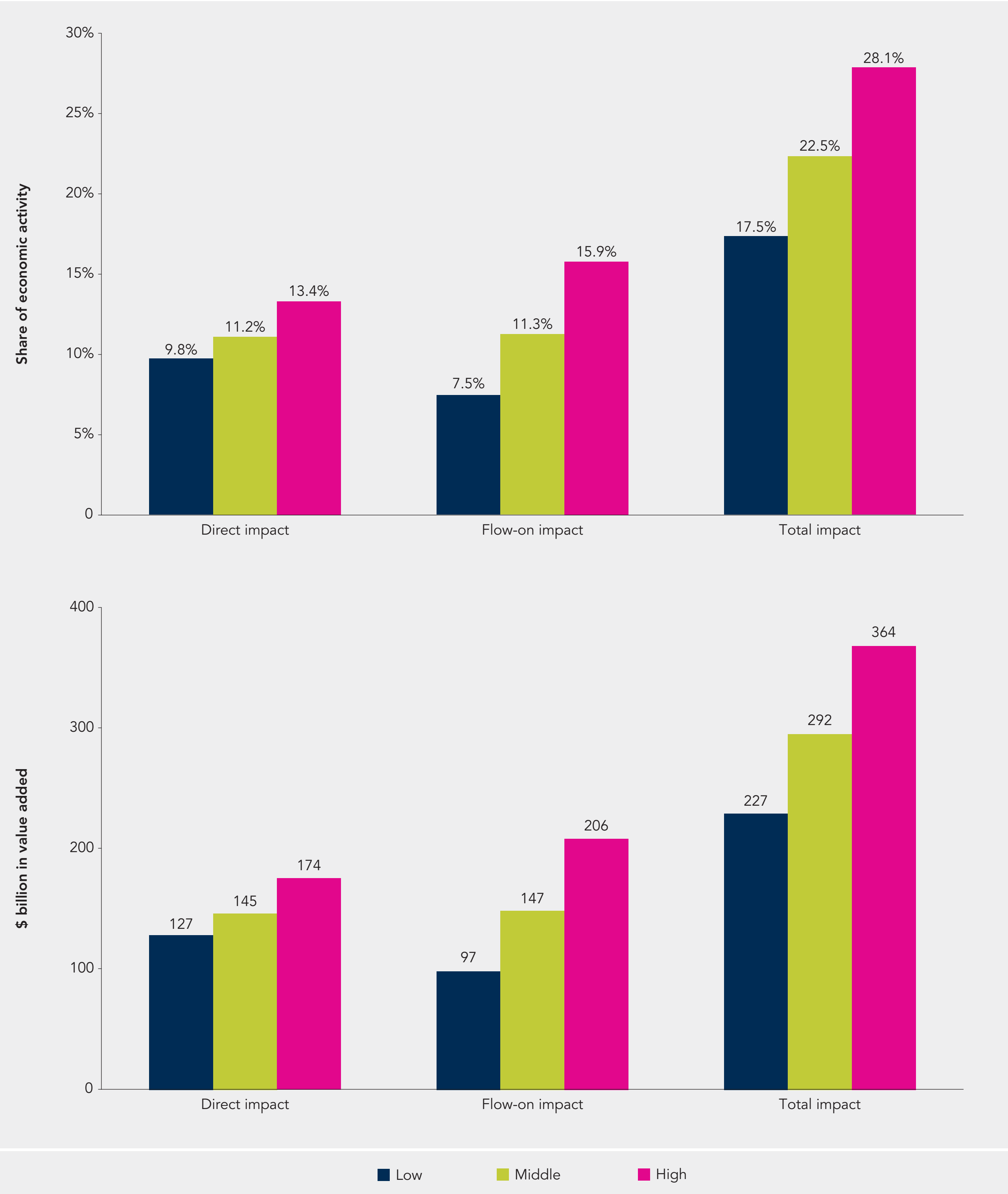
On the other hand, industries that produce output that is used narrowly or that is mostly exported create relatively small flow-on effects. For example, the magnitudes of the flow-on effects in the primary industries (including *agriculture* and *mining*) are relatively small.

CASE STUDY 7: PRODUCTIVITY AND MOBILE BROADBAND

This case study illustrates the impact of mobile broadband technology on productivity outside the APM sciences based sector.[12] It shows how physics and mathematics, by allowing complex data to be transmitted via radio waves, have created the relatively new product of mobile broadband. This has produced substantial productivity benefits throughout the economy.

12 Source for this case study: The CIE and Analysys Mason (2014).

Figure 7.1 The total impact of the APM sciences (% of economic activity, $ billion value added)



Note: To express APM sciences based GVA as a share of total GVA, we excluded from the total the GVA of the *ownership of dwellings* industry, as it is imputed by the ABS and the industry does not employ any people (it makes up 9% of the total).

Data source: The CIE.

Mobile technologies

The development of mobile internet technologies has had significant impacts on the economy. Mobile technologies have improved the productivity of the communications sector, producing flow-on benefits in other sectors through lower prices. However, mobile broadband services have also led to significant benefits for a wide range of other sectors of the economy through consumption of the services. The extent of the economic impacts of the sector and the associated indirect flow-on impacts were captured in the framework used in this report. The other benefits that the consumption of mobile broadband brings to the wider economy are additional to the estimates of the impact of the APM sciences reported in this study.

Technology development

Several innovations to 2G mobile phone technology enabled the development of mobile broadband through 3G and then 4G technologies. Those developments and technological advances can be attributed to research and innovation in physics and mathematical sciences disciplines.

Data optimisation and a dedicated data-only radio channel enable mobile networks to be used for larger data files. Higher order modulation allows faster speeds in areas of good-quality signal, and opportunistic scheduling increases the overall capacity of the network. 4G uses more antennas to create spatially separated paths and aggregated channels to increase data rates. A simplified core network resulted in less equipment per transmission, and lower latencies improved the user experience.

Service improvement

The rollout of 3G services gave mobile users access to a range of applications previously not accessible from mobile phones. It also led to the development of mobile broadband (mobile internet, not accessed through mobile phones, used for laptops and tablets). These services were made possible by the higher capacity and greater network functionality of the 3G network compared with the 2G network.

With the introduction of 3G networks and devices, consumers were able to receive multimedia files, access the internet, and use GPS navigation and other mobile applications on mobile phones. Mobile broadband modems enabled consumers to access the internet at speeds of up to 40 megabits per second without any fixed lines, increasing the flexibility, portability and usefulness of laptop computers and tablet devices.

Productivity of the mobile communications sector

From 2006 to 2013, the mobile communications sector achieved productivity growth of 11.3% per year (Table 7.1 and Figure 7.2). Without mobile broadband, growth would have been 6.7% per year[13] (CIE and Analysys Mason 2014). That growth was driven, at least in part, by technology improvements that enabled services to be delivered to consumers at lower cost to the suppliers.

Productivity growth accelerated more recently from 2010 to 2013, to a very high level. To put this growth in context, the Australian economy at its peak can achieve around 3% multifactor productivity growth per year and generally achieves growth well below that level.[14]

Prices of mobile communications products fell by an average of 8.4% per year over that period (CIE and Analysys Mason 2014). These price declines result in flow-on benefits, or indirect effects, to households and businesses.

Table 7.1 Mobile communications productivity growth and price trends, 2006 to 2013 (% per year)

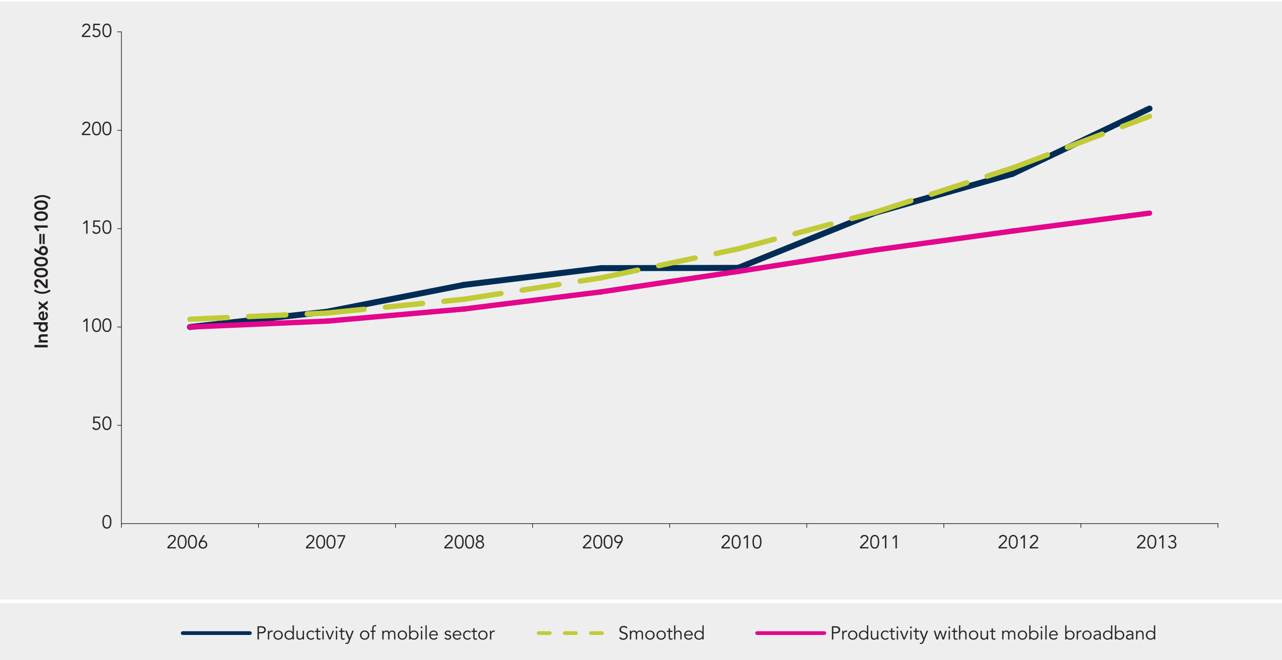
Item	2006 to 2013	2006 to 2010	2010 to 2013
Actual productivity growth	11.3	6.8	17.5
Productivity growth without mobile broadband	6.7	6.4	7.2
Prices	–8.4	–4.6	–13.3

Source: CIE and Analysys Mason (2014).

13 Estimated productivity growth without mobile broadband is based on relative output growth.

14 However, we could not realistically expect the Australian economy to achieve productivity growth at the same level as an emerging technology.

Figure 7.2 Productivity of the mobile communications sector, 2006 to 2013 (index: 2006 = 100)



Note: The smoothed productivity is based on fitting a second order polynomial.

Data source: The CIE and Analysys Mason (2014).

Productivity in other sectors

Mobile broadband has enabled businesses to change the way they operate, save time and save money. Businesses report that the take-up of mobile broadband has reduced business costs by 1.4% and saved 2.3% of employees' time, as well as improving the quality of their products and services and increasing their revenue (CIE and Analysys Mason 2014).[15] To put these figures into perspective, a time saving of 2.3% across the economy is equivalent to saving $15 billion in 2013.[16] These benefits from consumption are additional to the direct and indirect benefits of the APM sciences estimated in this study.

For most businesses and business activities, mobile communications are a small proportion (less than 20%) of the telecommunications spend. This indicates that very few businesses see mobile devices as their entire telecommunications solution. While they use mobile communications mainly for phone calls, emails and general internet access, many now use mobile devices for more sophisticated functions, such as accessing cloud services, using corporate applications, engaging customers, updating databases and managing stock.

15 Based on a survey of 1002 businesses of different sizes and in different sectors of the economy.

16 We calculated the value of time saving by applying this percentage to total wages and salaries for Australia.

CHAPTER 8

8. THE SOURCE OF ADVANCED PHYSICAL AND MATHEMATICAL SCIENTIFIC KNOWLEDGE

Chapter 6 explains that output produced using inputs that embody useful knowledge from the APM sciences makes up 11.2% of the Australian economy. This is the direct impact of those sciences.

This chapter discusses the ways in which the individual disciplines within the APM sciences contribute to that impact.

BREAKING DOWN THE SCIENCE-BASED SECTOR

As described in Chapter 2, there are three sources of useful knowledge within the APM sciences:

- the core disciplines (physics, chemistry and mathematics)
- the non-core disciplines (such as the earth sciences, which are based on a combination of principles from the core sciences)
- the direct combination of principles from core and non-core disciplines.

ACTIVITY BASED ON A SINGLE CORE SCIENCE DISCIPLINE

Of the 158 science-based industry classes in the ANZSIC classification system, 60 use inputs that embody useful knowledge from a single core discipline.

For those 60 industry classes, total GVA was $246 billion in 2012–13. The results of the workshop and industry consultations suggest that 19.0% of this GVA was based on the APM sciences. This means that the size of the sector based on a single core discipline was $47 billion (19.0% of $246 billion). This is 3.6% of the GVA of the economy as a whole.

Within the sector based on a single core science discipline, the most important industry classes are those in the finance, computing and transport industries based on mathematical sciences and those in the pharmaceuticals and plastics industries based on chemistry (Table 8.1).

ACTIVITY BASED ON COMBINATIONS OF THE CORE DISCIPLINES

Of the 158 science-based industry classes, eight are based only on the earth sciences and 90 are based on a combination of other APM sciences.

The earth sciences

For the eight industry classes based on the earth sciences only, total GVA was $19 billion in 2012–13. The results of the workshop and industry consultations suggest that 22.3% of this activity was produced from inputs that embody useful knowledge from the earth sciences. This means that the size of the sector based on earth sciences was $4.2 billion in 2012–13 (22.3% of $19 billion), or 0.3% of the economy as a whole.

The two key industry classes based on earth sciences outputs were:

- *mineral exploration*, which produced $2.5 billion of output from inputs that embody useful knowledge from the earth sciences in 2012–13
- *other heavy and civil engineering construction*, which produced $1.5 billion of output from such inputs in 2012–13.

Table 8.1 Sector based on a single core science discipline

Industry		Single core science discipline	Science-based GVA ($ billion)
6221	Banking	Maths	5
7000	Computer System Design and Related Services	Maths	5
4610	Road Freight Transport	Maths	4
1841	Human Pharmaceutical and Medicinal Product Manufacturing	Chemistry	2
6240	Financial Asset Investing	Maths	2
6330	Superannuation Funds	Maths	2
1912	Rigid and Semi-Rigid Polymer Product Manufacturing	Chemistry	2
All other industry classes based on a single core science discipline			25
Total			47
Total (share of total GVA)			3.6%

Note: To express APM sciences based GVA as a share of total GVA, we excluded from the total the GVA of the *ownership of dwellings industry*, as it is imputed by the ABS and the industry does not employ any people (it makes up 9% of the total).

Source: The CIE.

Output based on combinations of multiple disciplines

For the 90 industry classes based on combinations of principles from multiple disciplines, total GVA was $276 billion in 2012–13. The results of the workshop and industry consultations suggest that 34% of this activity was produced from inputs that embody useful knowledge translated from the APM sciences. This means that the size of the sector based on some combination of the APM scientific disciplines was $94 billion in 2012–13 (34% of $276 billion), or 7.3% of the economy as a whole.

Within the sector based on multiple APM scientific disciplines, the key industry classes are in mining (including *oil and gas extraction*, *iron ore mining* and *gold mining)*, financial services (including *general insurance*) and communications (Table 8.2).

Table 8.2 Sector based on multiple APM sciences disciplines

Industry class		APM scientific disciplines	Science-based GVA ($ billion)
700	Oil and Gas Extraction	Maths, physics, chemistry and earth sciences	16
6322	General Insurance	Maths, earth sciences	8
801	Iron Ore Mining	Maths, earth sciences	7
804	Gold Ore Mining	Maths, earth sciences	7
5801	Wired Telecommunications Network Operation	Maths, physics	7
8520	Pathology and Diagnostic Imaging Services	Maths, physics and chemistry	5
5802	Other Telecommunications Network Operation	Maths, physics	4
600	Coal Mining	Maths, physics, chemistry and earth sciences	4
All other industry classes based on combinations of disciplines			37
Total			94
Total (share of total GVA)			7.3%

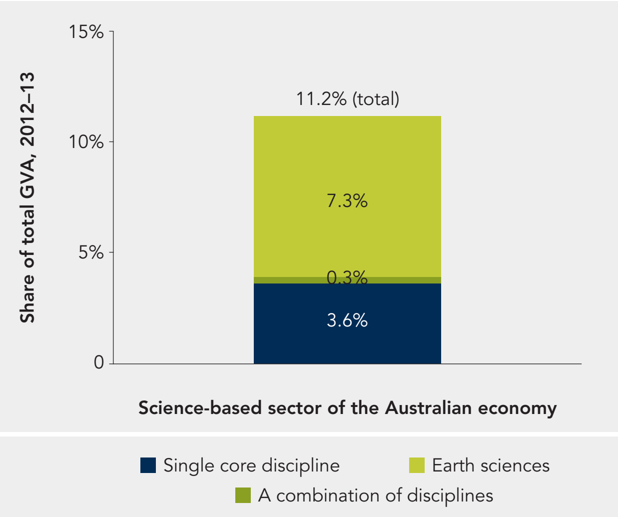
Note: To express APM sciences based GVA as a share of total GVA, we excluded from the total the GVA of the *ownership of dwellings* industry, as it is imputed by the ABS and the industry does not employ any people (it makes up 9% of the total).

Source: The CIE.

THE COMBINED RESULT

The results outlined above are summarised in Figure 8.1, which shows where the useful knowledge that directly underpins 11.2% of Australian economic activity comes from. Most of it comes from knowledge that is created by combining disciplines.

Figure 8.1 The sector based on the APM sciences, by source of useful knowledge (% of total GVA)



Note: To express APM sciences based GVA as a share of total GVA, we excluded from the total the GVA of the *ownership of dwellings* industry, as it is imputed by the ABS and the industry does not employ any people (it makes up 9% of the total).

Data source: The CIE.

CASE STUDY 8: WI-FI

This case study demonstrates multidisciplinary science's impact on productivity. It shows how physics and mathematics were combined to produce what is now a ubiquitous technology used by millions of businesses and households.[17]

The technology that became Wi-Fi was invented by Australian scientists working at the CSIRO's radio astronomy unit in the late 1980s and early 1990s. They needed to send large amounts of data between telescopes and their computers. They decided to send these data using radio waves (that is, wirelessly).

To send data using radio waves, they had to manage radio interference created by different sources (a physics problem). To do this, they created a complicated mathematical algorithm; that is, they solved the physics problem with mathematics.

The scientists realised that their wireless technology could have many other applications. They converted it to a small printed circuit that could be installed in personal computers. That step required specialist advanced electronic engineering—a capability that existed at CSIRO at that time. This incarnation of the technology became the basis of Wi-Fi technology used widely today.

17 Sources for this case study: Hans Bachor (ANU), Colley (2012) and CIE.

CHAPTER 9

9. AN EVALUATION OF OUR METHODOLOGY AND RESULTS

This chapter evaluates the methodology used in our study and the results.

EVALUATION OF THE DIRECT IMPACT

Our assessment of the direct impact of the APM sciences on the Australian economy had both strengths and limitations.

Strengths of our estimate of direct impact

Compared with the other studies described in Chapter 3, the CIE made a number of improvements to the methodology used to calculate the direct impact of science on the economy. The improvements are listed here. As they make our results more accurate, they are strengths of methodology.

We considered multiple APM scientific disciplines
This study considered multiple disciplines at once to determine the impact of science on the economy. Principles from different disciplines can be combined to create new knowledge that drives certain types of economic activity. By considering different disciplines simultaneously, we picked up this effect.

Other international studies have not considered multiple disciplines simultaneously. Therefore, when the authors of those studies have estimated the impact of a science, they have not considered how that science combines with other sciences to drive activity. In some cases, it is clear that have simply credited all science-based activity in a given industry to the particular science under consideration. In such cases, they have overestimated the impact of that science.

Although biology and the other life sciences were excluded from our study, it is unlikely that we have overallocated science-based activity to the APM sciences. This is because biology and the other life sciences tend to underpin different parts of the economy from the APM sciences.

We were careful not to overallocate activity to science
In both the workshop and the subsequent consultations with industry, the CIE carefully ensured that estimates of the importance of science to industry were not too strong. In other studies, many industries have been deemed to be '100%' based on science. In many cases, that is an implausible claim.

The estimated size of the science-based sector reflects the views of scientists and industry
To estimate the importance of science to each industry in the economy, we followed a three-step process. First, eminent scientists attended a workshop where the question was debated and resolved for all 506 industry classes. Second, for key industry classes, the workshop results were corroborated and developed using the views of industry stakeholders. This was a relatively thorough and robust process. Third, we carried out further cross-checking.

In most cases, the views of scientists and industry matched
One strength of our results is that the views expressed by the scientists at the workshop on the importance of science were close to the views of industry. The raw data from the workshop suggested that the APM sciences based sector makes up 12.8% of the economy. Incorporating the views of industry and other refinements brought that proportion down to 11.2%.

Limitations on our estimate of direct impact
We estimated the direct impact of the APM sciences as the quantity of output that is produced using inputs that embody useful knowledge derived from those sciences. This means that we probably underestimated it, as the APM

sciences create a number of beneficial direct impacts that are not recorded in current economic activity. This is a limitation on our results. The same limitation also exists in the results of other international studies.

Research aims to improve economic assets and thus drives future activity
Much scientific research is aimed at developing and improving economic assets. That work is thus aimed at driving future economic activity rather than current activity, so its impact is not recorded in current economic data. This study allowed for this effect by considering science from the past 20 years, although that approach is imperfect.

For example, the Academy has launched an initiative called 'Uncover', which aims to lift mineral exploration activity in Australia.

According to Blewett (2014), in a discussion published on Geoscience Australia's website, Australia's share of global expenditure on mineral exploration has declined in recent times because of a perception that Australia is a 'mature' supplier of minerals, with limited potential for new discoveries. In fact, most of Australia's landmass has not been effectively explored for mineral deposits because the techniques needed to explore some large regions have not been developed. Specifically, we cannot currently explore beneath the swathes of weathered rock (regolith) and sedimentary basins that cover 80% of Australia.

The Uncover initiative aims to drive collaboration among Australian researchers to develop techniques that will allow exploration in such regions. If Australia successfully develops those new techniques, the mining sector could grow significantly in the future.

Some science is aimed at avoiding a loss of economic activity rather than creating new activity
Some science is aimed at improving health and safety, or at avoiding or mitigating the impact of natural disasters. Rather than being intended to create new economic activity, it is aimed at avoiding a loss of activity (or minimising the loss associated with a natural disaster).

For example, what is the impact on the economy of Australia's tsunami warning system? Because it is impossible to observe that impact by considering only current economic activity, the answer in our methodology is zero.

Some science creates an impact by justifying regulations
Some science underpins regulations on business and consumer activity that (at least ostensibly) reduce output by preventing activity that would otherwise occur. If the regulations are justified (on the basis of a careful cost–benefit calculation), the science has a positive impact that is not quantified by considering current economic activity.

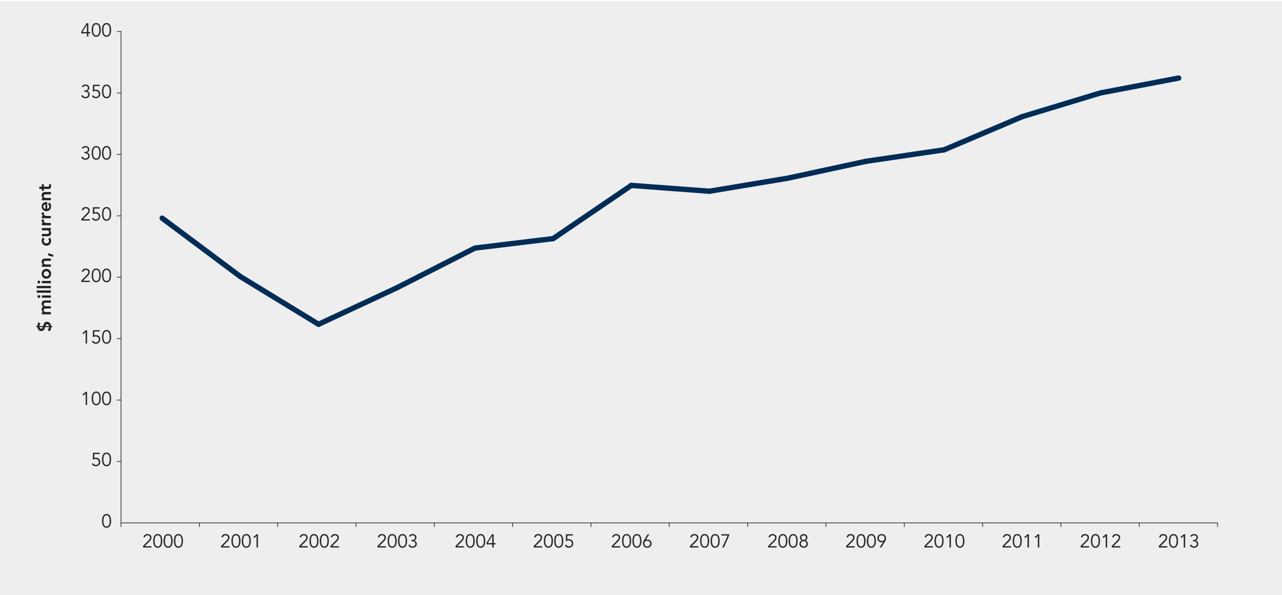
Consumer utility from new technology is poorly measured by economic statistics
Expenditure by consumers on technology products, that embody a significant amount of advanced science is a poor measure of the utility or pleasure they derive from those products because changes in the prices of the products do not reflect changes in the utility or pleasure.

Utility has increased significantly over time as new, improved products have replaced old ones. However, the price consumers pay for those products has not increased in line with the improvements. In fact, the creation of new products has often been associated with or facilitated by improved production methods, which have tended to contain price growth or even reduce prices (such as prices for computers). Therefore, individual consumer utility and prices (and therefore, individual expenditure) do not necessarily move in the same direction or by the same amount over time.

This is illustrated by data on imports of telecommunications equipment (Figure 9.1). Per capita imports grew on average by 3% per year between 2000 and 2013. However, it is reasonable to argue that the utility an Australian derives from their mobile phone has grown much more quickly than that. In particular, the utility we derive from our phones has increased sharply with the take-up of smartphones to replace earlier mobile phones. This is because the functionality of smartphones is vastly superior to that of the earlier technology.

Therefore, in the case of mobile phones, consumer utility or pleasure derived from new technology (and thus from science) is growing rapidly, but this is not captured in imports data (which form part of the national accounts and GDP).

Figure 9.1 Imports of telecommunications equipment, per capita, 2000 to 2013 ($ million, current prices)



Data sources: ABS; The CIE

The impact of some science that directly creates productivity gains and savings is not picked up

Some science is aimed at optimising the use of resources or saving resources. This means that the direct impact of that science could be savings through a reduced requirement for investment. This direct impact is not picked up by considering current output.

EVALUATION OF THE FLOW-ON IMPACT

As for our assessment of direct impacts, our methodology for assessing flow-on impacts includes both strengths and limitations.

Strength: we calculated the flow-on impact with an economy-wide model

We determined the flow-on or indirect impact of the economic sector based on the APM sciences using the economy-wide CIE-REGIONS CGE model. Within that model, the response of the economy to an imposed change is governed by the various effects and interactions that the model picks up (including changes in relative prices). Because of this feature, economists accept estimates of flow-on effects made with CGE models as reasonable.

In contrast, other studies have used multipliers derived from input–output tables to estimate the flow-on impact of the science-based sector.

Limitation: we probably underestimated the true flow-on impact

As explained in Chapter 5, we measured the flow-on impact of the APM sciences by determining the quantity of activity that was created by productivity gains and savings associated with the use of output from those sciences.

However, some APM scientific output not only creates savings for users, but also allows users to change their behaviour. This is a larger flow-on impact of the APM sciences that is not picked up by the CIE-REGIONS CGE model, so our result probably understates the true flow-on impact of those sciences.

For example, consider an advance in Wi-Fi technology. Firms that already use the internet to communicate with customers become more productive with the advance. This effect is picked up by the model. However, other firms may *change* the way they communicate with customers by increasing their use of the internet to take advantage of the advance. They will also receive a productivity boost, but the effect is not picked up in the model. This type of change is evident in the parts of the retail and food industries making more use of internet portals and phone apps (among other things), supported by more widely available and better Wi-Fi.

CHAPTER 10

10. HOW THE ADVANCED PHYSICAL AND MATHEMATICAL SCIENCES (APM SCIENCES) BASED SECTOR HAS PERFORMED COMPARED WITH OTHER SECTORS

Previous chapters describe the current size, economic impact and non-measured value of the APM sciences based sector of the economy. This chapter compares the performance of this sector over time with other sectors of the economy.

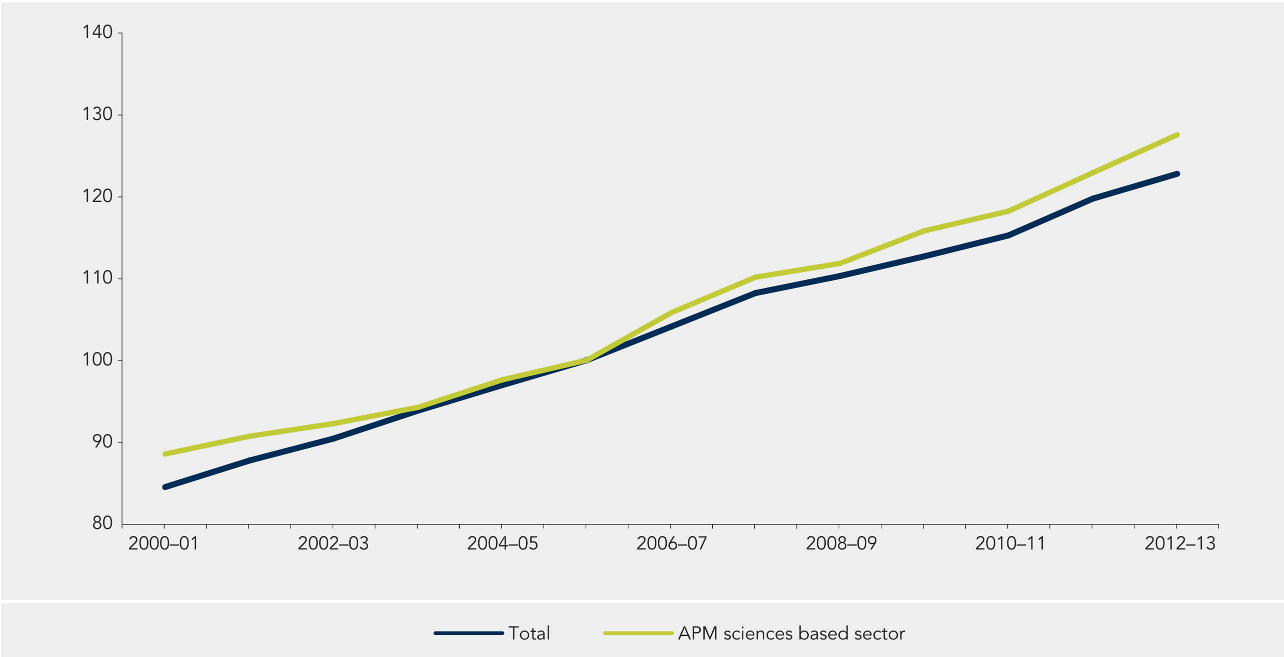
GROSS VALUE ADDED

Since 2005–06, the APM sciences based economy has grown by 3.5% per year, while the economy as a whole has grown by 3.0% per year (Figure 10.1).

Mining and *finance* are more important to the APM sciences based sector than they are to the economy as a whole. They have grown more quickly than average, and that has pushed up the growth rate of the APM sciences based sector compared with the rest of the economy.

On the other hand, *manufacturing*, *utilities* and *information, media and telecommunications* are also more important to the APM sciences based sector than they are to the economy as a whole. Those sectors have grown relatively slowly, pulling back the growth rate of the APM sciences based sector compared with the rest of the economy.

Figure 10.1 Gross value added, APM sciences based sector versus all sectors, 2000–01 to 2012–13 (index: 2005–06 = 100)



Note: Total GVA excludes GVA of the *ownership of dwellings* industry.

Data sources: ABS; The CIE.

PRODUCTIVITY

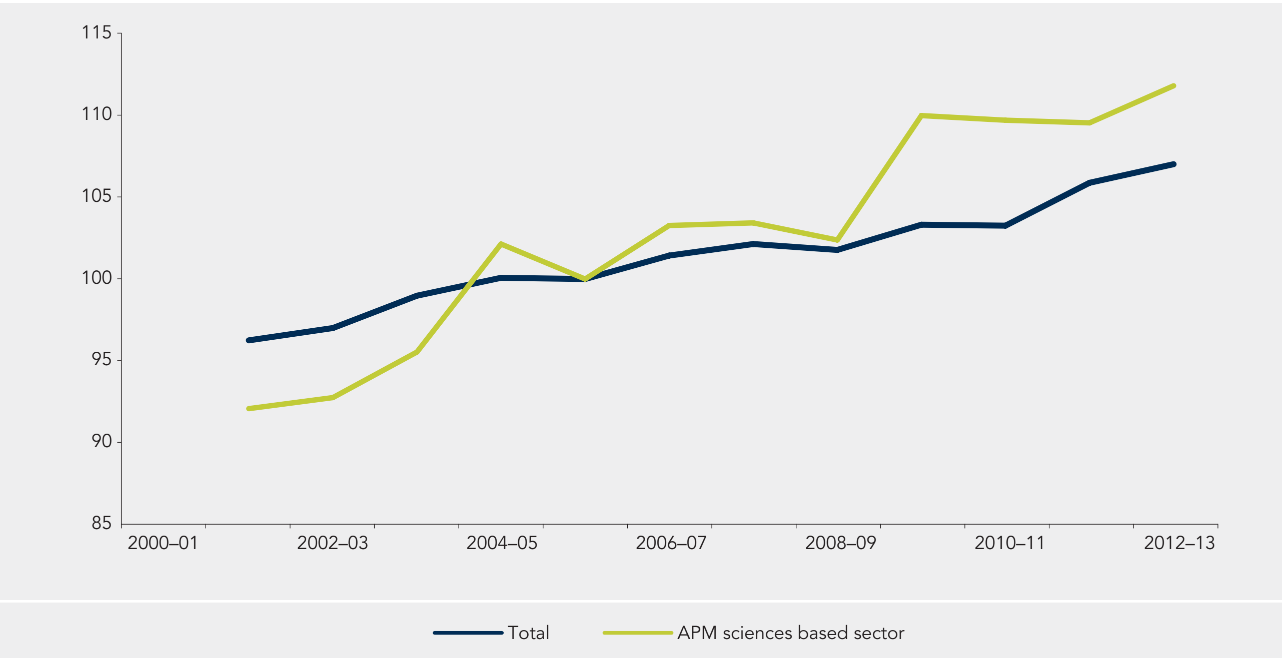
Since 2005–06, the relatively strong growth in the GVA of the APM sciences based sector has been due to relatively strong growth in productivity (GVA per worker) in the sector (Figure 10.2). This has been due to two factors.

First, productivity growth was relatively strong in the *information, media and telecommunications* and *finance* industries, which are both more important to the APM sciences based sector than they are to the economy as a whole. A strong surge in investment (boosting the capital stock per worker) and the invention of new technologies underpinned productivity growth in *information, media and telecommunications*, while recent weakness in financial conditions (due to the global financial crisis and its aftermath) forced the *finance* sector to boost its productivity growth.

Second, a number of industries in which productivity has been relatively weak are less important to the APM sciences based sector. They include *accommodation and food services* and *education and training*.

These two factors have offset the effect of relatively weak productivity growth in the *mining* and *utilities* industries in recent years. This has dragged on growth in productivity in the APM sciences based sector compared with the economy as a whole, as those two industries are relatively important to the sector. The slow productivity growth in mining and utilities has come despite a recent surge in investment in them. When this investment comes online and becomes productive, it is likely that productivity growth will pick up sharply. This should ensure that productivity growth in the APM sciences based sector will continue to outperform economy-wide productivity growth.

Figure 10.2 Real productivity, APM sciences based sector versus all sectors, 2000–01 to 2012–13 (index: 2005–06 = 100)



Note: Total GVA excludes the GVA of the *ownership of dwellings* industry.
Data sources: ABS; The CIE.

The flow-on effect of strong productivity growth in the APM sciences based sector

As discussed in the case study in Chapter 6, the *information, media and telecommunications* sector has experienced strong productivity growth recently. One reason for this is the development of mobile broadband technologies.

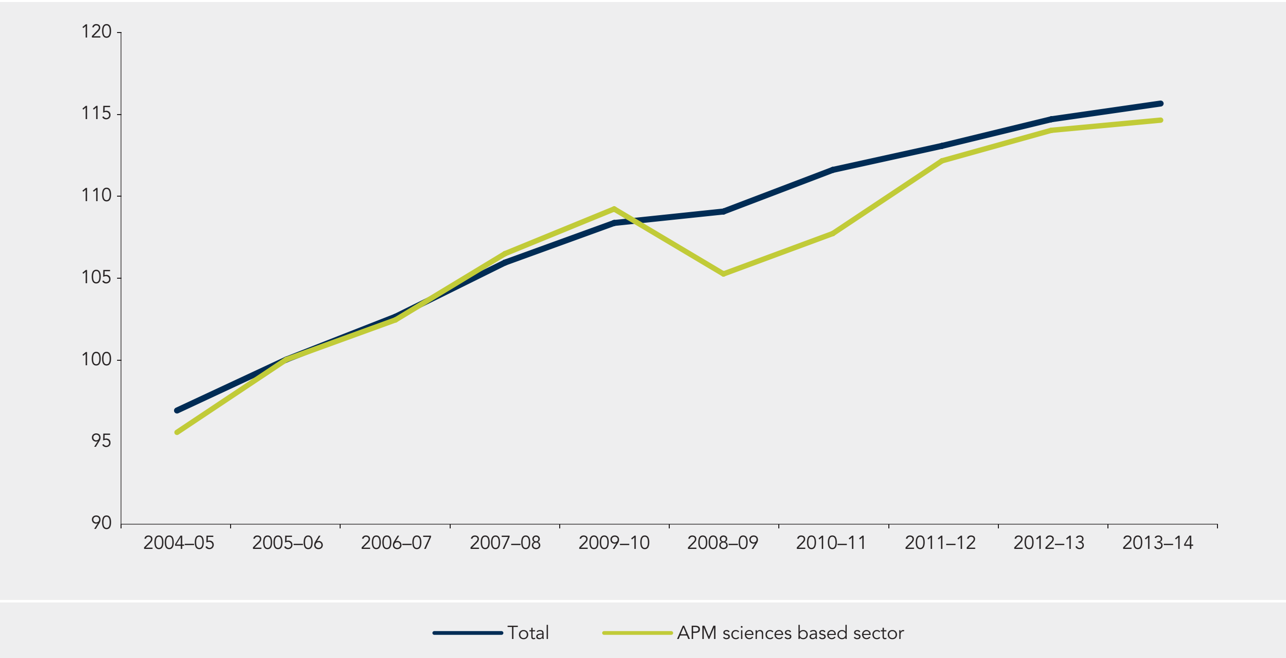
The development of those technologies has had substantial flow-on impacts right through the economy, boosting the economic performance, including the productivity, of non-science-based industries. Overall, if mobile broadband technologies had not been invented, productivity growth would have been weaker in both the APM sciences based sector and in the rest of the economy.

EMPLOYMENT

Since 2004–05, employment in the APM sciences based sector has continued to grow at a rate very similar to that in the rest of the economy (Figure 10.3). This strong growth is significant, given that the sector has also managed to steadily increase productivity per worker.

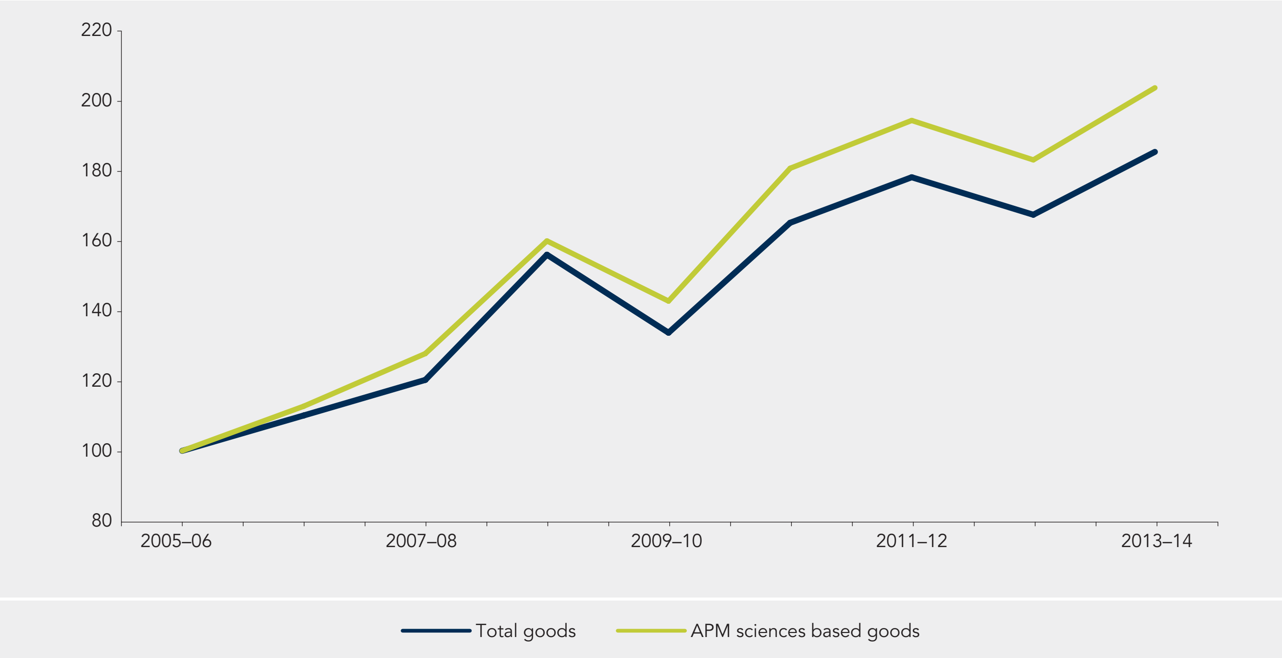
It is interesting to note that the effect of the global financial crisis from 2008–09 to 2009–10 can be seen in the employment outcomes for the APM sciences based sector. Employment in some of the key industry groups that make up the sector (including mining, parts of manufacturing, telecommunications and finance) was weak during the crisis. Importantly, however, employment in the sector continued to grow strongly after the crisis at about the same rate as the rest of the economy.

Figure 10.3 Employment, APM sciences based sector versus all sectors, 2000–01 to 2012–13 (index: 2005–06 = 100)



Data sources: ABS; The CIE.

Figure 10.4 Exports of goods, APM sciences based sector versus all sectors, 2000–01 to 2012–13 (index: 2005–06 = 100)



Data sources: ABS; The CIE.

GOODS EXPORTS

In recent years, growth in exports of goods based on the APM sciences has outpaced growth in total goods exports (Figure 10.4). This has been led by exports of mining goods based on the APM sciences.

It is true that overseas demand for such goods has been relatively strong, making it the key driver of this relatively strong growth.

However, it is also true that useful knowledge from the APM sciences is allowing us to supply this demand. That knowledge allows companies that operate in Australia to produce the goods that foreigners have the strongest demand for, and it is the APM sciences that are used to create the technology that supports competitiveness in these trade-exposed industries.

CHAPTER 11

11. HOW IMPORTANT ARE THE ADVANCED PHYSICAL AND MATHEMATICAL SCIENCES (APM SCIENCES) TO FUTURE ECONOMIC GROWTH?

According to the results reported here, the APM sciences directly underpinned around 11% of Australian economic activity in 2012–13 and, in total (including flow-on effects), contributed to just under 23% of economic activity.

This historical snapshot is significant. The extent to which a range of activities draws on advanced scientific knowledge is easily missed in day-to-day economic commentary. Indeed, how much our 'basic' industries, such as mining, draw on advanced science may surprise some Australians.

To what extent can this snapshot provide guidance about the future importance of science to our economy? Can it tell us anything about the relative importance of future science done in Australia, as opposed to the science embodied in imported goods and services?

While it is difficult to answer those questions precisely, a number of findings in this report suggest strongly that Australian science will remain crucial in the future.

This chapter examines four propositions:

- Modern economies draw on science, regardless of their overall economic structure.
- There is considerable value at stake in assessing the importance of science to the economy.
- There is wide acceptance that technology drives growth, and some expect that future growth will depend even more on technology.
- Australian science is integrated with global science.

SCIENCE UNDERPINS ADVANCED ECONOMIES

Table 11.1 compares the results of this study with the results of similar studies undertaken by Deloitte on the economies of Italy, the Netherlands and the United Kingdom. Our study gives an estimate of the size of the sector based on 'science', having considered multiple disciplines simultaneously. In contrast, each Deloitte study provides an estimate of the size of the sector based on a single scientific discipline.

In any economy, there is considerable overlap between the areas of the economy that are affected by single scientific disciplines. This is the nature of science, in which principles from different disciplines are combined to form useful knowledge that underpins different types of economic activity.

For example, the authors of Deloitte's (2014a) study on the impact of physics on the Italian economy assumed that the *manufacture of other inorganic chemicals* industry is 100% based on physics. It seems likely that those authors, if asked to repeat the study for the impact of chemistry, would identify the same industry as being 100% dependent on chemistry.

The implication of this is that, if other disciplines were added to the Deloitte studies listed in Table 11.1, the size of the science-based sector would not grow by very much. Therefore, it is reasonable to infer from the results in the table that science underpins between 10% and 15% of economic activity in the four economies listed (Australia, Italy, the Netherlands and the United Kingdom).

It is notable that those four economies have significantly different structures. In Australia, *non-manufacturing industry*, driven by mining, is more important, while in the European economies manufacturing is more important.

Table 11.1 Advanced economies: structure and dependence on science

Economy	Structure of economy: industry GVA as a share of GDP				Discipline	Size of science-based sector	Source
	Agriculture	Manufacturing	Non-manuf. industry	Services		(share of economy)	
Australia	2%	7%	20%	71%	Physics, chemistry, maths, earth sciences	11%	CIE
Italy	2%	15%	8%	74%	Physics	7%	Deloitte (2014a)
Netherlands	2%	13%	12%	74%	Maths	10%	Deloitte (2014b)
UK	1%	10%	11%	79%	Physics	9%	Deloitte (2012a)

Note: 'Non-manuf. industry' includes mining, construction and utilities.

Source: World Bank and as listed.

This suggests that, if an economy is an 'advanced' economy (one that provides its citizens with the standard of living enjoyed in Western Europe and Australia), 'science' underpins between 10% and 15% of economic activity, independently of the economy's overall structure.

THERE IS CONSIDERABLE VALUE AT STAKE

Between 17.5% and 28.1% of economic activity (our estimates, as reported in Figure 7.1) is a significant proportion at a single point in time. While this estimate represents a historical snapshot, it is reasonable to infer from it that a future without continued scientific development would involve lower economic growth simply because the proportion of growth that would otherwise come from growth in knowledge would be reduced.

While the exact magnitude of that reduction (in terms of annual growth, for example) cannot be inferred from our estimates, a 17.5–28.1% reduction over a period of at least 20 years would be a substantial potential loss.

Australia must avoid that loss.

THAT SCIENCE AND TECHNOLOGY DRIVE GROWTH IS WIDELY ACCEPTED

It is widely accepted that continued economic growth will require future scientific and technological development. New knowledge has been a fundamental driver of growth in the past and it is widely believed that it will remain so, indeed perhaps even more so (see, for example, Mokyr 2014, Cowen 2011 and Brynjolfsson and McAfee 2014).

While the economic growth seen in Australia today (and expected in the near future) is driven by growth in the available inputs (capital, labour and systems), the economy will continue to grow in the long term only if it continually finds more efficient ways to use those inputs. This includes using them to make new and better products. This observation arises from the fact that there are limits to the amount of activity we can extract from any given level of inputs, and there are limits on how much we can continue to accumulate inputs in the long term.

History (a good guide in this case) suggests that a substantial share of the useful knowledge that has contributed to prosperity and economic growth over time has been science-based in some way.

AUSTRALIAN SCIENCE IS INTEGRATED WITH GLOBAL SCIENCE

Science is a global enterprise, and science undertaken in Australia is a crucial part of that enterprise. While much of the science that underpins the Australian economy is available from international sources (we can 'buy' the science, as it is embodied in particular capital items or systems), our own research and scientific production remains crucial for a variety of reasons.

First, Australia's teaching links to the world through our international student programs depend on research done in Australia. As noted in Case study 9 on LED lights, many international scientists working in that field have been trained in Australia. However, discussions with experts in LED technology indicate clearly that it was the Australian research program that attracted those students in the first place. Teaching without the underlying research is not viable in the long term.

Second, the interpretation and application of global research itself requires research programs. While it may seem attractive to purchase advanced science off the shelf, that is not the way science works. Application and research are really the two ends of a continuum.

Finally, it is likely that Australia's circumstances will call for research, focused on particular issues, that might not necessarily be available internationally, and that important international findings may require specific application to Australian circumstances.

CASE STUDY 9: LED LIGHTS

This case study describes the invention of blue LED (light-emitting diode) lights.[18] That invention enabled the production of white LED lights that can be used for everyday lighting.

This is an example of a new idea that underpins long-run economic growth by creating new resources or allowing us to use existing resources more efficiently.

Importantly, LED lights are also an example of how Australian science is integrated into global science, and how sustained research in physics and chemistry (including in this case materials science) in Australia and overseas can lead to useful knowledge.

The advantages of LED lights

One measure of lighting efficiency is the number of lumens that a lighting source can produce per watt of input energy. A lumen is a unit of visible light; a watt is a unit of power.

Between the 1800s, when tallow and whale-oil candles and lamps were used for lighting, and the introduction of the first compact fluorescent globes in the early 1990s, light efficiency increased by around 70 000%, from 0.1 lumens/watt to around 70 lumens/watt (see Nordhaus 1998). LEDs, which have a potential efficiency of 300 lumens/watt, are a dramatic continuation of that trend.

The light we observe consists of travelling photons, which are elementary particles. Previous sources of lighting have usually used some form of combustion or physical effect (such as heating a tungsten filament with electric current) to generate photons and light.

The key advantage of LEDs is that they require much less energy to create photons. When activated by electrical current, they emit photons directly, without the need for combustion or other physical effects—dramatically reducing the loss of energy as heat.

The history of LEDs

The science behind LEDs stretches back to 1907 and the discovery of *electroluminescence* by British engineer Henry Joseph Round. Electroluminescence occurs when a material emits light in response to the passage of an electric current or the presence of a strong electric field. It is distinct from *incandescence*, which relies on heat and has been the traditional mechanism used in electrical lighting since the invention of the light globe (RSAS 2014).

The commercial development of LEDs occurred gradually over the following decades. The first ones were made from gallium arsenide in the 1950s and were then developed and refined to be more efficient and produce a wider range of light frequencies. Until 1968, the unit cost of LEDs was close to US$200, which meant that they had little practical use (Schubert 2003). By the 1970s, however, commercially successful LED devices at less than five cents each were produced by Fairchild Optoelectronics (Bausch 2011). As a result, LEDs became widely available and appeared in appliances and equipment such as calculators, traffic lights and vehicle indicators.

Until advances in the 1990s, the key disadvantage of LEDs was that they could not be used to create white light. They could produce some individual colours, including red and green, but the light humans need is white light. White light can be created by combining blue, red and green light, so to use LEDs for general lighting it was necessary to invent one that emitted blue light and could be combined with red and green LEDs to produce white light.

18 Sources for this case study: CIE, references cited, Professor Chennupati Jagadish (ANU).

The key material in blue LEDs is gallium nitride, and the challenge was to grow crystals of that material with the properties and form required for LED lights in commercial quantities. This was achieved by Isamu Akasaki, Hiroshi Amano and Shuji Nakamura in the 1990s, for which they were awarded the 2014 Nobel Prize in physics.

In awarding the prize, the Royal Swedish Academy of Sciences noted that white LED lights create a great benefit for humankind, because lighting accounts for 20–30% of our electrical energy consumption and LED lights need around 10 times less energy than ordinary light bulbs.

An Australian connection

While the Nobel Prize was awarded to a team of Japanese and American scientists, a considerable amount of the foundational work on growing the gallium nitride crystals took place in Australia (in particular, work led by the late Professor Trevor Tansley at Macquarie University). Research at Macquarie University also led to the establishment of BluGlass Limited,[19] an advanced semiconductor company that continues to develop breakthroughs in LED lighting and solar technology.

In addition, many of the scientists involved in manufacturing and developing LEDs in various countries have been trained in Australia, particularly at the ANU, and research in this field continues at the ANU's Department of Electronic Materials Engineering.[20]

The story of LEDs thus throws light on the complex linkages between Australian and international science.

An Australian application

One example of the benefits of LEDs in Australia has been the Sydney LED Light Program, which replaces conventional street and park lighting with LED lights. The program is reported to have saved almost $370 000 and reduced energy use more than 34% since March 2012 by rolling out more than 4100 energy-efficient LED lights. Nearly 6500 conventional lights are expected to be replaced with LEDs in New South Wales over the next three years (City of Sydney 2015).

19 See www.bluglass.com.au.

20 See www.anu.edu.au/CSEM/machines/MOCVD.htm.

APPENDIXES

APPENDIX 1: DETAILED RESULTS

Table A.1.1 shows the full detailed results of this study.

The ABS's 2006 ANZSIC industry classification system divides the Australian economy into 506 industry classes. For the 158 industry classes identified as science-based, Table A1.1 shows the total and science-based GVA in 2012–13 (measured in current prices, millions of Australian dollars), the science share (science-based GVA divided by total GVA), and the split of science-based GVA by discipline.

The 348 industry classes not identified as science-based are not shown.

Table A1.1 Detailed results of study, by ANZSIC industry class

Industry class		GVA ($m, 2012–13)		Science share	Discipline share of science				
		Total	Science-based		M	P	C	E	Gen
700	Oil and Gas Extraction	31 649	15 824	0.5	0.0	0.0	0.0	0.0	1.0
6322	General Insurance	18 990	7 596	0.4	0.5	0.0	0.0	0.5	0.0
801	Iron Ore Mining	23 458	7 037	0.3	0.3	0.0	0.0	0.7	0.0
804	Gold Ore Mining	16 747	6 699	0.4	0.3	0.0	0.0	0.7	0.0
5801	Wired Telecommunications Network Operation	16 399	6 560	0.4	0.7	0.3	0.0	0.0	0.0
8520	Pathology and Diagnostic Imaging Services	5 489	5 489	1.0	0.1	0.5	0.4	0.0	0.0
6221	Banking	53 641	5 364	0.1	1.0	0.0	0.0	0.0	0.0
7000	Computer System Design and Related Services	23 941	4 788	0.2	1.0	0.0	0.0	0.0	0.0
5802	Other Telecommunications Network Operation	6 961	4 177	0.6	0.7	0.3	0.0	0.0	0.0
4610	Road Freight Transport	18 590	3 718	0.2	1.0	0.0	0.0	0.0	0.0
600	Coal Mining	18 030	3 606	0.2	0.2	0.1	0.2	0.5	0.0
2630	Electricity Distribution	11 766	3 530	0.3	0.8	0.2	0.0	0.0	0.0
7711	Police Services	9 007	3 153	0.4	0.0	0.3	0.3	0.3	0.0
803	Copper Ore Mining	7 376	2 950	0.4	0.3	0.0	0.0	0.7	0.0
1090	Other Mining Support Services	3 661	2 746	0.8	0.0	0.4	0.0	0.6	0.0
1012	Mineral Exploration	2 461	2 461	1.0	0.0	0.0	0.0	1.0	0.0
1841	Human Pharmaceutical and Medicinal Product Manufacturing	2 369	2 369	1.0	0.0	0.0	1.0	0.0	0.0
6240	Financial Asset Investing	2 193	2 193	1.0	1.0	0.0	0.0	0.0	0.0
6330	Superannuation Funds	4 490	1 796	0.4	1.0	0.0	0.0	0.0	0.0
2611	Fossil Fuel Electricity Generation	8 822	1 764	0.2	0.1	0.4	0.4	0.1	0.0
1912	Rigid and Semi-Rigid Polymer Product Manufacturing	1 678	1 678	1.0	0.0	0.0	1.0	0.0	0.0
807	Silver-Lead-Zinc Ore Mining	4 070	1 628	0.4	0.3	0.0	0.0	0.7	0.0
4110	Supermarket and Grocery Stores	15 740	1 574	0.1	1.0	0.0	0.0	0.0	0.0
3109	Other Heavy and Civil Engineering Construction	15 401	1 540	0.1	0.0	0.0	0.0	1.0	0.0
4900	Air and Space Transport	7 282	1 456	0.2	1.0	0.0	0.0	0.0	0.0

Industry class		GVA ($m, 2012–13)		Science share	Discipline share of science				
		Total	Science-based		M	P	C	E	Gen
1892	Explosive Manufacturing	1 448	1 448	1.0	0.0	0.0	1.0	0.0	0.0
6910	Scientific Research Services	3 697	1 423	0.4	0.0	0.0	0.0	0.0	1.0
809	Other Metal Ore Mining	3 525	1 410	0.4	0.3	0.0	0.0	0.7	0.0
8401	Hospitals (except Psychiatric Hospitals)	13 020	1 302	0.1	1.0	0.0	0.0	0.0	0.0
806	Nickel Ore Mining	2 980	1 192	0.4	0.3	0.0	0.0	0.7	0.0
7600	Defence	3 555	1 173	0.3	0.0	0.0	0.0	0.0	1.0
2394	Aircraft Manufacturing and Repair Services	1 668	1 167	0.7	0.3	0.5	0.3	0.0	0.0
1831	Fertiliser Manufacturing	1 156	1 156	1.0	0.0	0.0	1.0	0.0	0.0
2619	Other Electricity Generation	1 110	1 110	1.0	0.8	0.2	0.0	0.0	0.0
1811	Industrial Gas Manufacturing	1 028	1 028	1.0	0.0	0.0	1.0	0.0	0.0
805	Mineral Sand Mining	2 566	1 026	0.4	0.3	0.0	0.0	0.7	0.0
4720	Rail Passenger Transport	5 003	1 001	0.2	1.0	0.0	0.0	0.0	0.0
1701	Petroleum Refining and Petroleum Fuel Manufacturing	995	995	1.0	0.0	0.0	1.0	0.0	0.0
1214	Wine and Other Alcoholic Beverage Manufacturing	3 959	990	0.3	0.1	0.0	0.9	0.0	0.0
1916	Paint and Coatings Manufacturing	930	930	1.0	0.0	0.0	1.0	0.0	0.0
149	Other Grain Growing	2 147	859	0.4	0.2	0.0	0.4	0.4	0.0
2640	On-Selling Electricity and Electricity Market Operation	2 678	804	0.3	1.0	0.0	0.0	0.0	0.0
4622	Urban Bus Transport (Including Tramway)	3 731	746	0.2	1.0	0.0	0.0	0.0	0.0
6922	Surveying and Mapping Services	1 482	741	0.5	0.1	0.1	0.0	0.8	0.0
4623	Taxi and Other Road Transport	3 614	723	0.2	1.0	0.0	0.0	0.0	0.0
1011	Petroleum Exploration	666	666	1.0	0.0	0.1	0.1	0.8	0.0
1919	Other Polymer Product Manufacturing	662	662	1.0	0.0	0.0	1.0	0.0	0.0
5511	Motion Picture and Video Production	1 099	660	0.6	1.0	0.0	0.0	0.0	0.0
145	Grain–Sheep or Grain–Beef Cattle Farming	3 105	652	0.2	0.2	0.0	0.1	0.7	0.0
1911	Polymer Film and Sheet Packaging Material Manufacturing	643	643	1.0	0.0	0.0	1.0	0.0	0.0
142	Beef Cattle Farming (Specialised)	5 297	636	0.1	0.1	0.0	0.1	0.8	0.0
9201	Casino Operation	3 138	628	0.2	1.0	0.0	0.0	0.0	0.0
802	Bauxite Mining	2 040	612	0.3	0.3	0.0	0.0	0.7	0.0
6310	Life Insurance	574	574	1.0	1.0	0.0	0.0	0.0	0.0

Industry class		GVA ($m, 2012–13)		Science share	Discipline share of science				
		Total	Science-based		M	P	C	E	Gen
4710	Rail Freight Transport	2 864	573	0.2	0.5	0.5	0.0	0.0	0.0
7520	State Government Administration	22 438	561	0.0	1.0	0.0	0.0	0.0	0.0
1821	Synthetic Resin and Synthetic Rubber Manufacturing	549	549	1.0	0.0	0.0	1.0	0.0	0.0
1851	Cleaning Compound Manufacturing	529	529	1.0	0.0	0.0	1.0	0.0	0.0
1813	Basic Inorganic Chemical Manufacturing	501	501	1.0	0.0	0.0	1.0	0.0	0.0
6925	Scientific Testing and Analysis Services	2 371	474	0.2	0.0	0.0	0.5	0.4	0.0
2620	Electricity Transmission	1 531	459	0.3	0.8	0.2	0.0	0.0	0.0
8591	Ambulance Services	2 142	428	0.2	1.0	0.0	0.0	0.0	0.0
2422	Communication Equipment Manufacturing	533	426	0.8	0.2	0.8	0.0	0.0	0.0
2412	Medical and Surgical Equipment Manufacturing	1 407	422	0.3	0.1	0.5	0.4	0.0	0.0
1709	Other Petroleum and Coal Product Manufacturing	410	410	1.0	0.0	0.0	1.0	0.0	0.0
131	Grape Growing	1 359	408	0.3	0.1	0.0	0.5	0.5	0.0
5101	Postal Services	3 922	392	0.1	1.0	0.0	0.0	0.0	0.0
7510	Central Government Administration	15 637	391	0.0	1.0	0.0	0.0	0.0	0.0
6321	Health Insurance	3 554	355	0.1	1.0	0.0	0.0	0.0	0.0
2110	Iron Smelting and Steel Manufacturing	1 747	349	0.2	0.1	0.5	0.4	0.0	0.0
1920	Natural Rubber Product Manufacturing	316	316	1.0	0.0	0.0	1.0	0.0	0.0
9209	Other Gambling Activities	1 549	310	0.2	1.0	0.0	0.0	0.0	0.0
1521	Corrugated Paperboard and Paperboard Container Manufacturing	773	309	0.4	0.0	0.2	0.8	0.0	0.0
1510	Pulp Paper and Paperboard Manufacturing	762	305	0.4	0.0	0.2	0.8	0.0	0.0
6223	Credit Union Operation	2 882	288	0.1	1.0	0.0	0.0	0.0	0.0
4000	Fuel Retailing	2 861	286	0.1	1.0	0.0	0.0	0.0	0.0
1852	Cosmetic and Toiletry Preparation Manufacturing	278	278	1.0	0.0	0.0	1.0	0.0	0.0
1812	Basic Organic Chemical Manufacturing	273	273	1.0	0.0	0.0	1.0	0.0	0.0
141	Sheep Farming (Specialised)	2 212	265	0.1	0.1	0.0	0.1	0.8	0.0
2612	Hydro-Electricity Generation	1 317	263	0.2	1.0	0.0	0.0	0.0	0.0
1524	Sanitary Paper Product Manufacturing	641	256	0.4	0.0	0.2	0.8	0.0	0.0

Industry class		GVA ($m, 2012–13)		Science share	Discipline share of science				
		Total	Science-based		M	P	C	E	Gen
2132	Aluminium Smelting	852	255	0.3	0.0	0.1	0.8	0.1	0.0
2419	Other Professional and Scientific Equipment Manufacturing	840	252	0.3	0.1	0.5	0.4	0.0	0.0
5921	Data Processing and Web Hosting Services	481	240	0.5	1.0	0.0	0.0	0.0	0.0
1832	Pesticide Manufacturing	225	225	1.0	0.0	0.0	1.0	0.0	0.0
5910	Internet Service Providers and Web Search Portals	1 116	223	0.2	0.8	0.2	0.0	0.0	0.0
1915	Adhesive Manufacturing	215	215	1.0	0.0	0.0	1.0	0.0	0.0
1899	Other Basic Chemical Product Manufacturing nec	214	214	1.0	0.0	0.0	1.0	0.0	0.0
1133	Cheese and Other Dairy Product Manufacturing	1 973	197	0.1	0.0	0.4	0.6	0.0	0.0
1842	Veterinary Pharmaceutical and Medicinal Product Manufacturing	187	187	1.0	0.0	0.0	1.0	0.0	0.0
1913	Polymer Foam Product Manufacturing	186	186	1.0	0.0	0.0	1.0	0.0	0.0
4810	Water Freight Transport	845	169	0.2	1.0	0.0	0.0	0.0	0.0
5102	Courier Pick-up and Delivery Services	1 632	163	0.1	1.0	0.0	0.0	0.0	0.0
7714	Correctional and Detention Services	3 072	154	0.1	0.0	1.0	0.0	0.0	0.0
159	Other Crop Growing nec	383	153	0.4	0.3	0.0	0.1	0.6	0.0
144	Sheep–Beef Cattle Farming	1 245	149	0.1	0.1	0.0	0.1	0.8	0.0
301	Forestry	747	149	0.2	0.3	0.0	0.0	0.8	0.0
2811	Water Supply	10 287	139	0.0	0.0	0.2	0.8	0.0	0.0
203	Onshore Aquaculture	130	130	1.0	0.3	0.0	0.3	0.4	0.0
6222	Building Society Operation	1 279	128	0.1	1.0	0.0	0.0	0.0	0.0
2010	Glass and Glass Product Manufacturing	1 256	126	0.1	0.0	0.0	1.0	0.0	0.0
2139	Other Basic Non-Ferrous Metal Manufacturing	402	121	0.3	0.0	0.3	0.4	0.3	0.0
5220	Airport Operations and Other Air Transport Support Services	2 955	118	0.0	0.5	0.5	0.0	0.0	0.0
152	Cotton Growing	357	107	0.3	0.1	0.0	0.5	0.5	0.0
160	Dairy Cattle Farming	2 655	106	0.0	0.1	0.0	0.1	0.8	0.0
151	Sugar Cane Growing	1 053	105	0.1	0.1	0.0	0.4	0.5	0.0
2411	Photographic Optical and Ophthalmic Equipment Manufacturing	111	100	0.9	0.1	0.5	0.4	0.0	0.0
2133	Copper Silver Lead and Zinc Smelting and Refining	330	99	0.3	0.0	0.3	0.4	0.3	0.0

Industry class		GVA ($m, 2012–13)		Science share	Discipline share of science				
		Total	Science-based		M	P	C	E	Gen
1212	Beer Manufacturing	960	96	0.1	0.3	0.0	0.7	0.0	0.0
2812	Sewerage and Drainage Services	463	93	0.2	0.0	0.3	0.7	0.0	0.0
6229	Other Depository Financial Intermediation	904	90	0.1	1.0	0.0	0.0	0.0	0.0
510	Forestry Support Services	431	86	0.2	0.3	0.0	0.0	0.8	0.0
2700	Gas Supply	2 089	84	0.0	1.0	0.0	0.0	0.0	0.0
1523	Paper Stationery Manufacturing	205	82	0.4	0.0	0.2	0.8	0.0	0.0
411	Rock Lobster and Crab Potting	407	81	0.2	0.7	0.0	0.0	0.3	0.0
1529	Other Converted Paper Product Manufacturing	201	80	0.4	0.0	0.2	0.8	0.0	0.0
1131	Milk and Cream Processing	347	69	0.2	0.0	0.0	1.0	0.0	0.0
6230	Non-Depository Financing	640	64	0.1	1.0	0.0	0.0	0.0	0.0
3312	Cereal Grain Wholesaling	281	56	0.2	1.0	0.0	0.0	0.0	0.0
419	Other Fishing	234	47	0.2	0.0	0.0	0.0	1.0	0.0
201	Offshore Longline and Rack Aquaculture	200	40	0.2	0.0	0.0	0.0	1.0	0.0
1620	Reproduction of Recorded Media	200	40	0.2	0.5	0.5	0.0	0.0	0.0
2122	Steel Pipe and Tube Manufacturing	152	38	0.3	0.0	0.5	0.5	0.0	0.0
8922	Nature Reserves and Conservation Parks Operation	186	37	0.2	0.7	0.0	0.0	0.3	0.0
123	Vegetable Growing (Outdoors)	1 739	35	0.0	0.3	0.0	0.3	0.4	0.0
412	Prawn Fishing	171	34	0.2	0.0	0.0	0.0	1.0	0.0
5021	Pipeline Transport	295	29	0.1	0.0	0.5	0.5	0.0	0.0
2591	Jewellery and Silverware Manufacturing	265	26	0.1	0.0	0.0	0.7	0.3	0.0
1522	Paper Bag Manufacturing	60	24	0.4	0.0	0.2	0.8	0.0	0.0
202	Offshore Caged Aquaculture	117	23	0.2	0.0	0.0	0.0	1.0	0.0
1313	Synthetic Textile Manufacturing	92	23	0.3	0.0	0.5	0.5	0.0	0.0
2391	Shipbuilding and Repair Services	1 140	23	0.0	0.3	0.4	0.3	0.0	0.0
1132	Ice Cream Manufacturing	217	22	0.1	0.0	0.4	0.6	0.0	0.0
139	Other Fruit and Tree Nut Growing	1 035	21	0.0	0.3	0.0	0.3	0.4	0.0
1829	Other Basic Polymer Manufacturing	20	20	1.0	0.0	0.0	1.0	0.0	0.0
8910	Museum Operation	123	19	0.2	0.0	0.5	0.5	0.0	0.0
5309	Other Warehousing and Storage Services	2 866	14	0.0	1.0	0.0	0.0	0.0	0.0
414	Fish Trawling Seining and Netting	51	10	0.2	0.0	0.0	0.0	1.0	0.0

Industry class		GVA ($m, 2012–13)		Science share	Discipline share of science				
		Total	Science-based		M	P	C	E	Gen
2029	Other Ceramic Product Manufacturing	185	9	0.1	0.0	0.5	0.5	0.0	0.0
136	Citrus Fruit Growing	451	9	0.0	0.3	0.0	0.3	0.4	0.0
2293	Metal Coating and Finishing	871	9	0.0	0.0	0.5	0.5	0.0	0.0
2034	Concrete Product Manufacturing	871	9	0.0	0.0	0.5	0.5	0.0	0.0
1891	Photographic Chemical Product Manufacturing	9	9	1.0	0.0	0.0	1.0	0.0	0.0
133	Berry Fruit Growing	397	8	0.0	0.3	0.0	0.3	0.4	0.0
2393	Railway Rolling Stock Manufacturing and Repair Services	791	8	0.0	0.3	0.4	0.3	0.0	0.0
143	Beef Cattle Feedlots (Specialised)	66	8	0.1	0.1	0.0	0.1	0.8	0.0
2922	Waste Remediation and Materials Recovery Services	661	7	0.0	0.0	0.5	0.5	0.0	0.0
134	Apple and Pear Growing	307	6	0.0	0.3	0.0	0.3	0.4	0.0
413	Line Fishing	22	4	0.2	0.0	0.0	0.0	1.0	0.0
2921	Waste Treatment and Disposal Services	417	4	0.0	0.0	0.5	0.5	0.0	0.0
135	Stone Fruit Growing	181	4	0.0	0.3	0.0	0.3	0.4	0.0
1411	Log Sawmilling	456	2	0.0	1.0	0.0	0.0	0.0	0.0
137	Olive Growing	99	2	0.0	0.3	0.0	0.3	0.4	0.0
146	Rice Growing	3	1	0.3	0.1	0.0	0.6	0.3	0.0
2142	Aluminium Rolling, Drawing, Extruding	263	1	0.0	0.0	0.5	0.5	0.0	0.0
132	Kiwifruit Growing	12	0	0.0	0.3	0.0	0.3	0.4	0.0
2149	Other Basic Non-Ferrous Metal Product Manufacturing	119	0	0.0	0.0	0.5	0.5	0.0	0.0
2141	Non-Ferrous Metal Casting	32	0	0.0	0.0	0.5	0.5	0.0	0.0
Total	--	540 417	144 950	0.268	--	--	--	--	--

Total economy[b]	1 296 550	
Science sector, share of total economy		11.2%

Key: M=Maths, P=Physics, C=Chemistry, E=Earth Sciences, Gen=General

a GVA is measured in current prices, millions of Australian dollars in 2012–13

b Total GVA (economy wide GVA) excludes GVA of industry *ownership of dwellings*

Source: The CIE.

Table A1.2 shows the detailed results of this study, split by industries in the CIE-REGIONS 58 model.

A1.2 Detailed results of the study, by CIE-REGIONS classification

Industry	GVA (2012–13, $m)		Science share
	Total	Science-based	
Livestock	14 485	1 165	0.1
Crops	11 503	1 718	0.1
Livestock–Crops	3 105	652	0.2
Forestry	512	86	0.2
Fishing	4 585	519	0.1
Coal	18 030	3 606	0.2
Oil & gas	31 649	15 824	0.5
IronOre	23 458	7 037	0.3
OthMetalOres	39 305	15 518	0.4
OthMining	9 587	5 873	0.6
FoodDrnkTob	26 746	1 374	0.1
TCF	2 811	23	0.0
WoodProds	3 594	2	0.0
PaperProds	2 642	1 057	0.4
Printing	3 661	40	0.0
PetrolProds	1 405	1 405	1.0
Chemicals	8 218	8 218	1.0
RubPlasProds	5 267	5 198	1.0
ONmMinProds	2 280	135	0.1
Cement	3 375	9	0.0
IronSteel	2 573	387	0.2
OtherMetals	3 283	476	0.1
MetalProds	11 381	9	0.0
TransEquip	9 031	1 198	0.1
OtherEquip	12 511	1 200	0.1
OtherManuf	2 650	26	0.0
Electricity (coal, gas & oil)	8 822	1 764	0.2
ElecHydro	1 317	263	0.2
ElecOther	1 110	1 110	1.0
ElecSupply	15 975	4 792	0.3
GasSupply	2 089	84	0.0
WaterSupply	10 750	232	0.0
Construction	117 588	1 540	0.0
WholeTrade	61 815	56	0.0
RetailTrade	69 182	1 860	0.0
MechRepairs	13 116	0	0.0

Industry	GVA (2012–13, $m)		Science share
	Total	Science-based	
HotelsCafes	34 779	0	0.0
RoadPass	7 795	1 469	0.2
RoadFreight	18 590	3 718	0.2
RailPass	5 003	1 001	0.2
RailFreight	2 864	573	0.2
PipeLine	381	29	0.1
Ports	3 505	0	0.0
TransprtSrvc	23 460	570	0.0
WaterFreight	845	169	0.2
ShipCharter	868	0	0.0
Air Pass & Freight	10 236	1 575	0.2
Communicate	42 168	11 860	0.3
Finance	124 795	18 449	0.1
BusinessSrvc	181 062	7 427	0.0
Dwellings	2 986	0	0.0
GovAdmin	79 576	5 431	0.1
Education	69 935	0	0.0
Health	97 760	7 219	0.1
OthServices	30 534	1 004	0.0
Total	**1 296 550**	**144 950**	**0.1**
Science-based share of economy	**11.2%**		

Note: GVA for 2012–13 measured in current prices and millions of Australian dollars

Source: The CIE.

APPENDIX 2: THE CIE-REGIONS MODEL

The CIE-REGIONS model is a general equilibrium model of the Australian economy. It was developed by the CIE based on the publicly available MMRF-NRA model developed by the Productivity Commission (PC 2006b).

Some of the key aspects of this model that made it especially suited for this task are as follows:

- It uses the latest input–output table.
- It provides a detailed account of industry activity, investment, imports, exports, changes in prices, employment, household spending and savings and many other factors.
  - It identifies 58 industries and commodities (Table A2.1).
- It accounts for Australia's six states and two territories as distinct regions, including specific details about the budgetary revenues and expenditures of each of the eight state and territory governments and the Australian Government (the government finances in CIE-REGIONS align as closely as practicable to the ABS government finance data).
  - It includes a detailed treatment of the fiscal effects of the goods and services tax (GST).
  - It specifically accounts for major taxes, including land taxes, payroll taxes, stamp duties and other charges at the state level, as well as income taxes, tariffs, excise, the GST and other taxes at the federal level (Table A2.2).
  - It traces the impact of transfers between governments.
- It accounts for differing economic fundamentals in the states (for example, the mining boom in Western Australia and Queensland).
- It can produce results on employment and value added at the regional level.
- It can be run in a static or dynamic mode. The dynamic version allows analysis to trace impacts over time as the economy adjusts, which is particularly useful over the medium and longer terms.

The CIE has used CIE-REGIONS to analyse the impacts of a range of policy changes, including state tax reform, local infrastructure development, and industrial development strategies.

Table A2.1 CIE-REGIONS industries/commodities and margin services

1	Livestock	30	Electricity generation—hydro
2	Crops	31	Electricity generation—other
3	Forestry	32	Electricity supply
4	Fishing	33	Gas supply
5	Coal	34	Water and sewerage services
6	Oil	35	Construction
7	Gas	36	Wholesale trade
8	Iron ore	37	Retail trade
9	Other metal ores	38	Mechanical repairs
10	Other mining	39	Hotels, cafes and accommodation
11	Food, beverage and tobacco	40	Road passenger transport
12	Textiles, clothing and footwear	41	Road freight transport
13	Wood products	42	Rail passenger transport
14	Paper products	43	Rail freight transport
15	Printing	44	Pipeline transport
16	Petroleum products	45	Ports services
17	Chemicals	46	Transport services
18	Rubber and plastic products	47	Water freight transport
19	Other non-metal mineral products	48	Ship charter
20	Cement and lime	49	Air passenger transport
21	Iron and steel	50	Air freight transport
22	Other non-ferrous metals	51	Communication services
23	Metal products	52	Finance
24	Transport equipment	53	Business services
25	Other equipment	54	Ownership of dwellings
26	Other manufacturing	55	Government administration and defence
27	Electricity generation—coal	56	Education
28	Electricity generation—gas	57	Health
29	Electricity generation—oil	58	Other services
Margin services			
Gas supply (part of commodity 33)		Pipeline transport (part of commodity 44)	
Wholesale trade (part of commodity 36)		Ports services (part of commodity 45)	
Retail trade (part of commodity 37)		Water freight transport (part of commodity 47)	
Hotels, cafes & accommodation (part of commodity 39)		Air freight transport (part of commodity 50)	
Road freight transport (part of commodity 41)		Finance (part of commodity 52)	
Rail freight transport (part of commodity 43)			

Source: CIE-REGIONS database.

A2.2 Federal and state taxes

Federal taxes	State, territory and local government taxes
Goods and services tax (GST)	Payroll tax
Sales taxes	Land tax
Excises and levies	Municipal rates
Labour income tax	Fire surcharges
Company income tax	Stamp duties on
Non-residents income tax	- insurance
Import duties	- financials
Export taxes	- motor vehicle
	- residential property
	- non-residential property
	- other

Source: CIE-REGIONS database.

APPENDIX 3: EXPERT WORKING GROUP MEMBERSHIP

Emeritus Professor Hans Bachor, FAA	The Australian National University Chair—National Committee for Physics
Professor Kenneth Baldwin	The Australian National University
Professor Nigel Bean	The University of Adelaide
Professor Allan Chivas, FAA	University of Wollongong
Mr Stephen Horn	Statistical Society of Australia
Professor Carole Jackson	Curtin University
Dr Naomi Mathers	The Australian National University
Dr Phil McFadden, FAA	Australian Academy of Science
Professor Paul Mulvaney, FAA	The University of Melbourne Chair—National Committee for Chemistry
Professor Sue O'Reilly, FAA	Macquarie University Chair—National Committee for Earth Sciences
Professor Geoff Prince	The University of Melbourne
Professor Robert Robinson	Australian Nuclear Science and Technology Organisation
Professor Mark von Itzstein, FAA	Griffith University

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ABBREVIATIONS AND ACRONYMS

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The Academy	Australian Academy of Science
ANU	Australian National University
APM sciences	advanced physical and mathematical sciences
CGE	computable general equilibrium
CIE	Centre for International Economics
COFS	Centre for Offshore Foundation Systems
CSIRO	Commonwealth Scientific and Industrial Research Organisation
GDP	gross domestic product
GPS	Global Positioning System
GST	goods and services tax
GVA	gross value added
HVCCC	Hunter Valley Coal Chain Coordinator
IT	information technology
LED	light-emitting diode
NSQ	non-school qualification
PIG	pipeline inspection gauge, pipeline intervention gadget
R&D	research and development
STEM	science, technology, engineering and mathematics
UWA	University of Western Australia