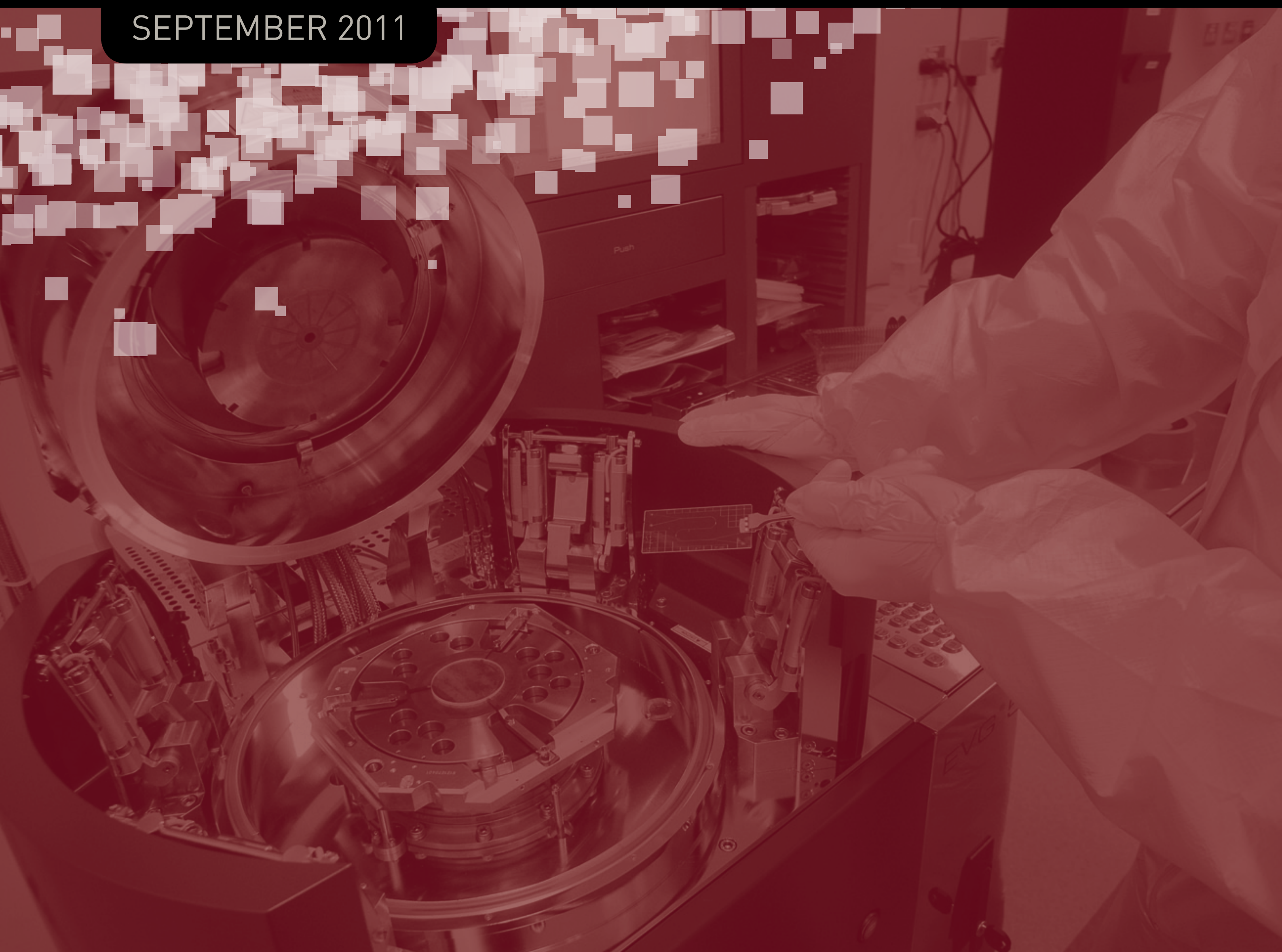
Australian Government

Department of Innovation
Industry, Science and Research

2011 STRATEGIC ROADMAP FOR AUSTRALIAN RESEARCH INFRASTRUCTURE

SEPTEMBER 2011



ISBN 978 1 921916 19 9

DIISR 11/108

CONTENTS

IMAGES

Cover (background)	Bond chamber (Courtesy of the Australian National Fabrication Facility)
Cover (left to right)	Human endothelial cells attaching and growing in a microfluidic artificial microvascular network (Courtesy of the Australian National Fabrication Facility, credit Dr Lien Chau and members of Cooper-White group) Gemini North Laser Guide Star System (Courtesy of the Gemini Observatory and Association of Universities for Research in Astronomy)[1] Tsunami buoy (Courtesy of the Integrated Marine Observing System and CSIRO) High-resolution plant phenomics centre growth chamber (Courtesy of the Australian Plant Phenomics Facility) Samples being loaded into an atom probe instrument (Courtesy of the Australian Microscopy and Microanalysis Research Facility and The University of Sydney) A stained section of mouse epididymis as seen under the microscope (Courtesy of the Australian Phenomics Network)
Image A	Heavy Ion Accelerator laser alignment of large area multi-wire proportional counter detectors (Courtesy of the Heavy Ion Accelerator Facility and Australian National University)
Image B	Maia x-ray microprobe elemental image of micronutrients in a mature barley grain (Courtesy of CSIRO, credit Babasola Ajiboye, University of Adelaide)
Image C	Gemini South looking up from the observing floor (Courtesy of the Gemini Observatory and Association of Universities for Research in Astronomy)[2]
Image D	Deploying an Integrated Marine Observing System acoustic receiver (Courtesy of the Integrated Marine Observing System, credit Rob Harcourt)
Image E	Tumbarumba flux tower (Courtesy of the Terrestrial Ecosystem Research Network, credit R. Leuning, CSIRO)
Image F	Trays of core samples scanned into the National Virtual Core Library (Courtesy of AuScope)
Image G	Solar Panels, similar to those to be used at the Moree Solar Farm (Courtesy of the Moree Solar Farm)
Image H	Australian Square Kilometre Array Pathfinder antennas at the Murchison Radio-astronomy Observatory (Courtesy of CSIRO, credit Brian Boyle)
Image I	Stirred tank reactor for mammalian cells (Courtesy of Ausbiotech, credit Morgan Brown)
Image J	Stained section of mouse seminal vesicles as seen under the microscope (Courtesy of the Australian Phenomics Network)
Image K	Plant accelerator (Courtesy of the Australian Plant Phenomics Facility)

1 www.gemini.edu/gallery/v/gn/lgs/lgs_from_cfht_green_sm.jpg.html
2 www.gemini.edu/gallery/v/gs/interiors/20060131_gs_sunset_sky.jpg.html

Image L	Examining a daisy specimen in the Australian National Herbarium (Courtesy of the Atlas of Living Australia and CSIRO)
Image M	Colour-enhanced scanning electron micrograph of the surface of a peppermint gum leaf (Courtesy of the Australian Microscopy and Microanalysis Research Facility, credit Mana Gharun)
Image N	Inside the storage ring (Courtesy of the Australian Synchrotron)
Image O	Silica preform manufacture, the first stage in making silica optical fibres (Courtesy of the Institute for Photonics and Advanced Sensing, credit Peter Fisher)
Image P	Global Navigation Satellite Systems (GNSS) at Lord Howe Island (Courtesy of AuScope)
Image Q	Satscan whole drawer imaging station at the Australian National Insect Collection (Courtesy of the Atlas of Living Australia, credit Gavin Jackson, Canberra Photography)
Image R	Poliovirus, the first four million atom complete virus capsid simulation, as performed on supercomputers (Courtesy of the Victorian Life Sciences Computation Initiative, credit Jason Roberts, Victorian Infectious Diseases Reference Laboratory, Melbourne Health)

EXECUTIVE SUMMARY

Research infrastructure is a prime determinant of Australia's ability to undertake excellent and world-leading research. A strong and thriving research sector is a fundamental component of an advanced innovation system. Many ideas that inspire transformative innovation are born from research.

Innovation is the key to increasing Australia's productivity and competitiveness, and to responding to the most significant challenges of our time, such as our changing climate, national security, hunger and disease. Innovation provides the avenue to position Australia as a leading player in the high value and sustainable industries of the future.

Over the last seven years, a strategic, collaborative approach for considering Australia's national research infrastructure needs has proven highly effective. This approach has provided national research infrastructure facilities and platforms that are supporting research to address global economic, social and environmental challenges.

A coordinated approach to investment encourages greater collaboration, between both organisations and researchers, stimulating multidisciplinary research and fostering linkages. This in turn facilitates entirely new research outcomes.

Strategic roadmapping exercises have been instrumental in developing a shared vision of national research infrastructure requirements. The *2011 Strategic Roadmap for Australian Research Infrastructure* (2011 Roadmap) has been developed through extensive consultation with researchers and other stakeholders and builds on the previous Roadmaps released in 2006 and 2008.

The 2011 Roadmap articulates the priority research infrastructure areas of a national scale (capability areas) to further develop Australia's research capacity and improve innovation and research outcomes over the next five to ten years. The capability areas have been identified through considered analysis of input provided by stakeholders, in conjunction with specialist advice from Expert Working Groups.

Capability areas identified in previous Roadmaps have received substantial investments through the National Collaborative Research Infrastructure Strategy, the Super Science Initiative and the Education Investment Fund. Facilities established under these initiatives are delivering high quality research infrastructure services to a broad base of users, and a number have been recognised as world-leading initiatives. The 2011 Roadmap highlights the need to sustain high performing facilities that remain a national priority, to ensure the availability of infrastructure services on which researchers and the sector can rely. Future funding for national, collaborative research infrastructure will be subject to Australian Government budget decision processes.

The push towards greater integration has been an important theme throughout the consultation process. There is a clear need to connect both existing and future facilities to assist in the seamless provision of generic and specific research infrastructure services. Greater integration and linkages will underpin improved collaboration, both nationally and internationally, thus enabling researchers to utilise systems approaches to tackle today's challenges.

In order to highlight the linkages, the capability areas in this Roadmap have been organised into two broad groups: those that are targeted towards specific research outcomes, and those that are enabling for research across a range of areas.

In implementing the capability areas outlined in this Roadmap, it will be important to consider the principles in the National Research Infrastructure Council's *Strategic Framework for Research Infrastructure Investment*, to ensure the maximum contribution to national prosperity.

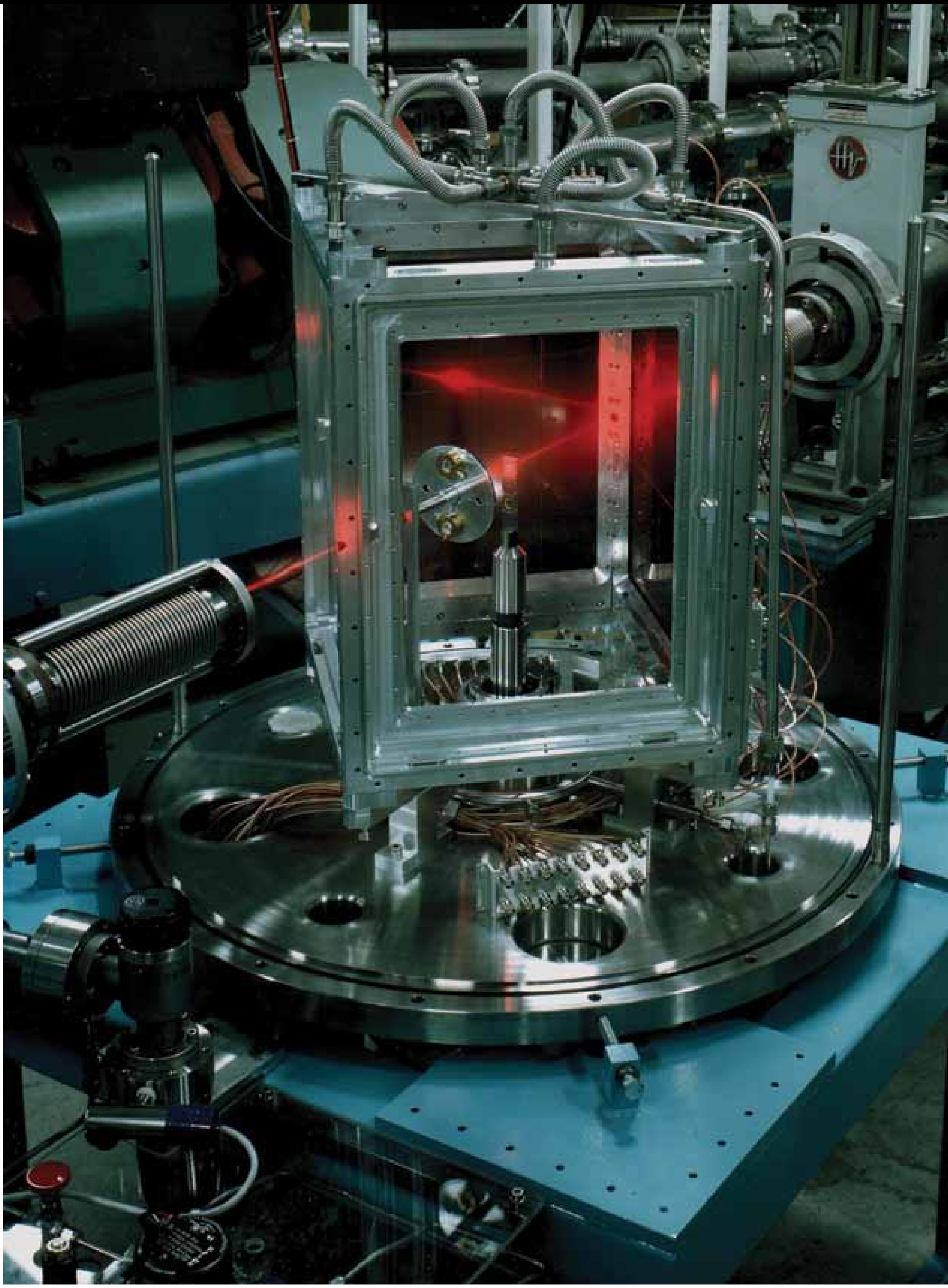


Image A

INTRODUCTION

RESEARCH INFRASTRUCTURE AS PART OF THE INNOVATION SYSTEM

The *2011 Strategic Roadmap for Australian Research Infrastructure* (2011 Roadmap) articulates the priority areas for national, collaborative research infrastructure over the next five to ten years (capability areas). The priorities outlined in the 2011 Roadmap are an important element in strengthening Australia's innovation system.

In *Powering Ideas: An Innovation Agenda for the 21st Century*[3] the government focused on the role of innovation in making Australia more prosperous and competitive. The Australian Government is committed to a richer, fairer and greener Australia, built on a broad based and sustainable national economy.

> *Our capacity for invention and discovery depends on the strength of our national innovation system. This is the system we use to harness the creativity of our people, to transform great ideas into great results for the community, the economy and the environment. Genius is wasted if you can't capture it and apply it to the real world. That's what the national innovation system does.*
>
> *Entrepreneurs, policy-makers, researchers, workers, and consumers are all part of the innovation system. One way to make the system stronger is by strengthening its constituent parts. The other is by strengthening the links between those parts. Australia needs to do both.*[4]

The elements involved in achieving a world-class innovation system are shown in Figure 1.

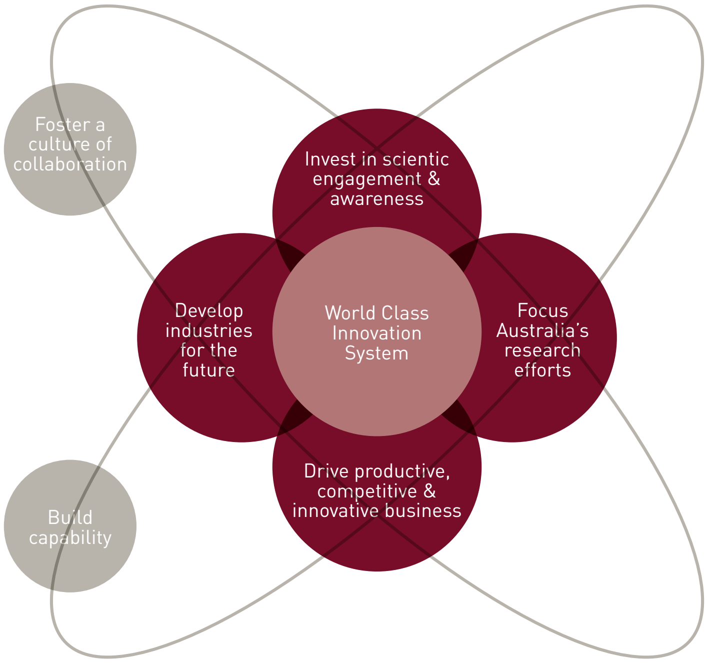


Figure 1 – Elements of a world-class innovation system

3 www.innovation.gov.au/Innovation/Policy/Pages/PoweringIdeas.aspx
4 www.innovation.gov.au/Innovation/Policy/Documents/PoweringIdeasExecutiveSummary.pdf, pg 1

Innovation is critical to economic growth. For example, the Organisation for Economic Co-operation and Development (OECD) has noted that 'developing the innovative effort, including formal research and development, is the sine qua non of growth'[5]. The recently published *2011 Australian Innovation System Report* states that innovation-active Australian businesses are 41 per cent more likely to report increased profitability than businesses that don't innovate[6].

While a stable macroeconomic environment provides the overall basis for growth, the OECD has also noted that government policy to foster innovation and enhance human capital is needed for growth to occur. On the policy front specifically, there is a clear, increasing imperative for a coordinated, coherent approach to maximising the innovation dividend.

It is widely accepted in Australia and internationally that public investment in research plays a significant role in building innovation capacity and driving productivity[7, 8, 9]. In Australia's case in particular, the OECD has identified that public and private research and development exert significant effects on our national productivity[10].

Innovation is not only about the economy. *Powering Ideas* looked forward over ten years to position us as a nation to respond to the big challenges of our time, including climate change and social disadvantage, and to capture the opportunities being opened up by advances in healthcare and communications.

A robust and thriving research sector underpins Australia's innovation system. The knowledge resulting from excellent research leads to new discoveries, applications and technologies. Research breakthroughs can solve seemingly intractable issues and will drive the development of industries for the future.

As the Australian Academy of Science observes

> *If we support our best research, and train our young people so they can take up the skilled jobs that will be generated, Australia will be able to emerge from the present period as a knowledge-based, economically competitive and intellectually vibrant country.*[11]

For research to flourish in Australia, a number of factors need to be present. A vital component of a high performing research sector is the availability of quality research infrastructure. Australian researchers, if they are to participate in addressing the big, complex research problems facing Australia and the world, need to be equipped with the right research tools.

> *Research undertaken in Australia's industry, public, not for profit and university sectors is inextricably linked to Australia's overall innovation performance. In order to best meet the needs of the nation, investments in research infrastructure should be prioritised based on areas in which Australia seeks to develop leading research capability and be balanced by a focus on innovation outcomes and the contribution that research makes to national productivity and prosperity.*[12]

World-class research infrastructure boosts the productivity of Australia's researchers and is essential to support the conduct of excellent research. It is the platform that enables Australia to

---

5 www.oecd.org/dataoecd/2/31/39374789.pdf
6 www.innovation.gov.au/Innovation/Policy/Pages/AustralianInnovationSystemReport2011.aspx, pg 53
7 Productivity Commission, 2007, www.pc.gov.au/projects/study/science/docs/finalreport
8 National Academy of Sciences, 2010, www.aps.org/policy/reports/upload/rags-revisited.PDF
9 Martin and Tang, 2007, www.erawatch-network.eu/reports/sewp161.pdf
10 www.oecd.org/dataoecd/2/31/39374789.pdf
11 Australian Academy of Science submission in response to the 2011 Roadmap Discussion Paper
12 Australian Industry Group submission in response to the Strategic Framework for Research Infrastructure Investment Discussion Paper

contribute at the forefront of science and research, and increases the attractiveness of Australian researchers as collaborators and Australia as a location for international research projects. Beyond direct research outcomes, research infrastructure furthers skills development and facilitates collaboration, thus compounding the benefits.

With finite resources, Australia needs to target its investments in research infrastructure through considering its priorities in both a national and an international context. The 2011 Roadmap is an important part of this process.

Definition of research infrastructure

Research infrastructure is defined by the National Research Infrastructure Council (NRIC)[13] in the *Strategic Framework for Research Infrastructure Investment* (Strategic Framework) as follows:

> *Research infrastructure comprises the assets, facilities and services which support research across the innovation system and which maintain the capacity of researchers to undertake excellent research and deliver innovation outcomes.*

The Strategic Framework is included in full at **Appendix A**.

PURPOSE OF THE 2011 ROADMAP

The 2011 Roadmap has been developed through extensive consultation with the research sector to identify strategic priorities for Australia over the next five to ten years. It builds on the direction that Australia has taken in national, collaborative infrastructure planning and investment in recent years.

The *2004 Final Report of the National Research Infrastructure Taskforce*[14] identified the need for a collaborative, rather than competitive, approach to planning medium to large research infrastructure investments.

The first Strategic Roadmap[15], developed in 2006, identified the priority capabilities for the investments under the National Collaborative Research Infrastructure Strategy (NCRIS). The *2008 Strategic Roadmap for Australian Research Infrastructure*[16] formed the basis for the Australian Government's 2009 Super Science Initiative funded from the Education Investment Fund (EIF)[17].

NCRIS[18] and the Super Science Initiative[19] have resulted in investments of over $1.4 billion in a broad range of research infrastructure at the national, collaborative scale. These investments have been successful in achieving the creation of improved national research capability through the development of new facilities and leveraging existing capacity. As these facilities have matured, they are delivering on the promise of strategic, national, collaborative investment.

These investments have been complemented by funding of $746 million over three competitive rounds for research infrastructure through the EIF. Further detail on the facilities supported under NCRIS, Super Science and EIF is available through the following webpage: www.innovation.gov.au/Science/ResearchInfrastructure/Pages/default.aspx.

13 www.innovation.gov.au/Science/ResearchInfrastructure/Pages/NRIC.aspx
14 http://ncris.innovation.gov.au/Documents/NRIT_Report.pdf
15 http://ncris.innovation.gov.au/Documents/2006_Roadmap.pdf
16 http://ncris.innovation.gov.au/Documents/2008_Roadmap.pdf
17 www.deewr.gov.au/HigherEducation/Programs/EIF/Pages/default.aspx
18 www.innovation.gov.au/Science/ResearchInfrastructure/Pages/NCRIS.aspx
19 www.innovation.gov.au/Science/ResearchInfrastructure/Pages/SuperScience.aspx

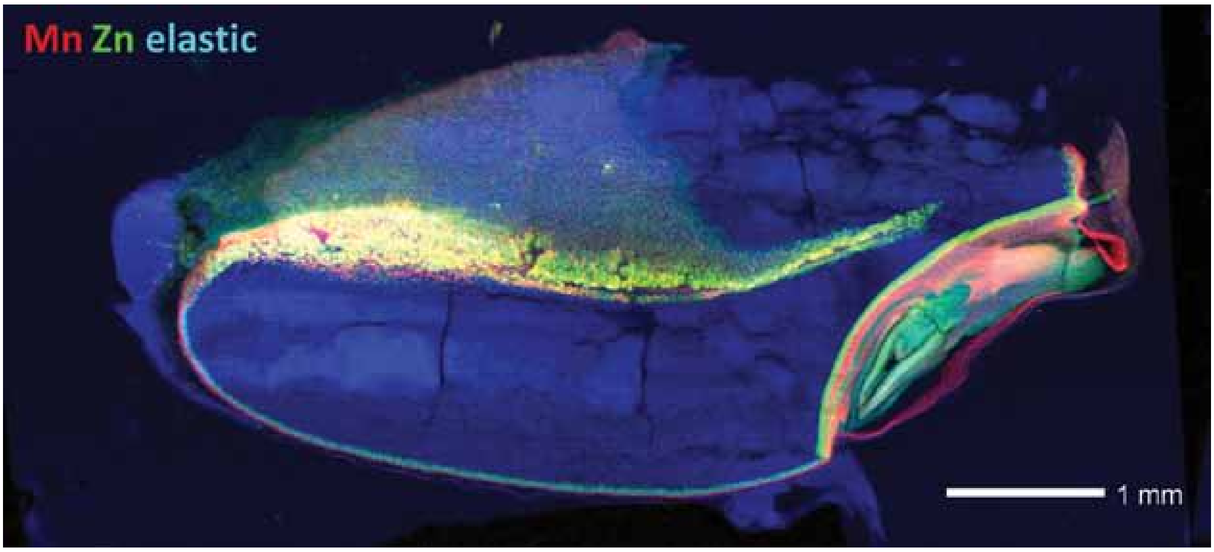


Image B

Funding under NCRIS concluded on 30 June 2011 and funding from the Super Science Initiative is fully allocated and will conclude on 30 June 2013. The 2011 Roadmap outlines priority areas for national, collaborative research infrastructure if there were to be additional funding available through any future government programs.

The use of roadmapping as a mechanism for prioritising research infrastructure has been validated by the NCRIS evaluation[20] and more recently through the extensive consultations undertaken during the development of the Strategic Framework and this Roadmap.

The strategic, consultative approach used in previous roadmapping exercises established a number of priority capability areas for research infrastructure investment. In the development of the 2011 Roadmap, the research community was asked to consider future research trends, their strategic importance to Australia and the research infrastructure required to capitalise on these trends. This meant looking beyond the current needs of today's research, to the types of research infrastructure services that a broad range of researchers would use in the future.

This consultation has led to the identification of the priority capability areas identified in this Roadmap that require national, collaborative research infrastructure support.

A driving principle in identifying capability areas was that the research infrastructure provided should support a large number of researchers, often across a range of disciplines. It should be noted that not every research area or discipline requires infrastructure of a national, collaborative scale.

The areas identified describe broad capability requirements that require ongoing or increased investment. Where types of infrastructure are identified in the Roadmap, this is primarily used to describe the type of capacity required rather than the specific investment.

The individual capability area descriptions in this Roadmap do not generally contain specific reference to existing facilities. However, it is recognised and has been acknowledged through submissions to the Roadmap process that the majority of the existing investments are achieving strong outcomes and have the support of the research community. Capitalising on these investments will be important into the future.

20 www.innovation.gov.au/Science/ResearchInfrastructure/Pages/NCRIS.aspx

Whilst the Roadmap looks forward over the next ten years, it is important periodically to consider new and emerging areas in the research environment requiring national scale investment. Therefore it is recommended that consultative roadmapping is undertaken approximately every three years.

The 2011 Roadmap has been developed in consultation with a broad range of stakeholders, using the specialist advice of six Expert Working Groups (EWGs), and with strategic oversight from NRIC. An outline of the process is at **Appendix B**, including details of the membership of the EWGs.

SCOPE OF THE 2011 ROADMAP

This Roadmap is primarily concerned with national research infrastructure at a medium to large scale, identifying capabilities likely to have a strategic impact on research in Australia.

The Strategic Framework identifies three broad categories of research infrastructure investments.

- Local – research infrastructure which could be expected to be owned and operated within a single institution.
- National – research infrastructure on a scale generally not appropriate to be owned or operated by a single institution and which often supports collaborative research and is generally regarded as part of the national research capability.
- Landmark – large scale facilities (which may be single-site or distributed) that serve large and diverse user communities, are generally regarded as part of the global research capability, and engage national and international collaborators in investment and access protocols.

The 2011 Roadmap covers capability areas that are of a national scale and generally require investment in the order of $20 million to $100 million over five years for each capability area.

Investments in research infrastructure at the institutional level are generally funded through each organisation's own resources, supported by block grants. At the project level, organisations may collaborate on larger scale initiatives that may not be possible individually. Programs such as the Australian Research Council's Linkage Infrastructure Equipment and Facilities scheme[21] provide a key funding mechanism for this type of cooperative initiative. Institutional or project level investments generally fit within the local category.

NRIC has proposed that research infrastructure involving a minimum of $100 million in funding from the Australian Government (for capital and other associated costs) over the first five years of operation be considered as Landmark research infrastructure. NRIC has proposed a 'Process to identify and prioritise Australian Government Landmark research infrastructure investments'[22] which is currently under consideration by the government as part of broader deliberations relating to research infrastructure.

The development of additional capacity within existing landmark facilities has been considered and identified within a number of capability areas in the 2011 Roadmap.

21 www.arc.gov.au/ncgp/lief/lief_default.htm
22 www.innovation.gov.au/Science/Documents/LandmarkDiscussionPaper.pdf

DIRECTIONS IN RESEARCH INFRASTRUCTURE

The research infrastructure landscape is changing in response to a number of drivers, including changes in research practice. An integrated approach is increasingly required to answer many of today's complex problems. Research is therefore becoming more collaborative and interdisciplinary, in order to capitalise on a range of skills and knowledge. In Australia, this trend is being supported by the investments over the last ten years in national, collaborative research infrastructure.

The growing volume and complexity of data has emerged as a dominant driver of change. This is sometimes referred to as the data deluge[23]. Research infrastructure is needed to maximise research outcomes from the diverse range of data collected in the past, present and future.

> *A fundamental characteristic of our age is the rising tide of data – global, diverse, valuable and complex. In the realm of science, this is both an opportunity and a challenge.*[24]

Australia's ongoing research success will depend on the development and improved management of national and global research data environments, to ensure that data is interoperable, openly accessible and discoverable. The dividends from this will include greater efficiency and effectiveness in research and, at a more transformational level, an ability to tackle new system level problems of national and global significance.

Solving these complex scientific, social, economic or environmental problems will increasingly require researchers to have access to a multitude of data sets from a diverse range of sources. Australia is leading the way on innovative methods to link and integrate data; however this remains a challenging area.

Greater coordination is required to realise the substantial benefit offered by integrated data analysis and re-use, especially in light of the significant increase in the rate of data being captured, as well as the range of disciplines and capability areas depending on data. The related issues around the development of standards, access protocols, ensuring security and ongoing curation of data also demand further attention.

It is clear that the management and use of data is a pervasive issue through all capability areas identified in the 2011 Roadmap.

Another driver is the recognition of the significant value obtained through considering research infrastructure needs through a strategic, national, collaborative approach, as acknowledged in the 2010 evaluation of NCRIS. This approach meets the needs of a broad base of users, rather than a single institution or discipline, and has supported novel, collaborative research activities that are already, or have the potential to be, world-class. Many of the facilities created through this approach have been recognised internationally as cutting-edge, innovative and highly effective.

The NCRIS approach has provided a platform for cultural change in the conduct of research, supporting collaborative behaviour and the exploitation of technological advances, and it is important to continue to support this direction into the future.

23 www.dest.gov.au/NR/rdonlyres/D15793B2-FEB9-41EE-B7E8-C6DB2E84E8C9/15103/From_Data_to_Wisdom_Pathways_data_man_forAust_scie.pdf
24 http://cordis.europa.eu/fp7/ict/e-infrastructure/docs/hlg-sdi-report.pdf

Feedback to the Roadmap process has confirmed a shift in research towards systems thinking, and the need for research infrastructure to recognise the convergence of various discipline areas. It is therefore imperative that the research infrastructure system becomes more integrated and provides the tools researchers need in a seamless manner.

It is recognised that stronger interoperation and integration of infrastructure will depend on both investment in physical infrastructure and in the linkages between infrastructure service providers and the broader research community.

Sustaining the services on which researchers have come to rely is vital to keeping Australia's researchers at the forefront of scientific discovery. The facilities established through previous Roadmaps have received significant investment and maximum benefit will be realised if ongoing support for these facilities is provided.

In summary, areas of critical importance at this stage in the further development of the national, collaborative research infrastructure system are:

- a continued and deepening focus on data integration and interoperability, supported by infrastructure both within and between capabilities
- the need to ensure research infrastructure integrates generic and specific services in a way that is seamless to the researcher
- the need to further connect and integrate both the infrastructure that has been funded to date and any new facilities
- the need to sustain existing investments, to ensure a predictable, stable and continuous set of infrastructure services on which researchers and other infrastructure providers can rely.

A NATIONAL APPROACH

In order to develop a world-class, integrated suite of research infrastructure, a national approach needs to be taken. This approach must consider the responsibilities and investments across a range of jurisdictions and the publicly funded research sector.

A number of federal, state and territory portfolios fund and host research infrastructure, including health, energy, education, heritage, arts, environment and agriculture. In addition, a wide range of facilities funded as a result of previous Roadmaps, such as high performance computing infrastructure to support climate research, will be increasingly relied upon by agencies other than the Department of Innovation, Industry, Science and Research (DIISR). The increasingly interdisciplinary nature of research and recognition of the potential to re-use data across multiple fields raise new inter-jurisdictional challenges to implementing capabilities described in this Roadmap.

Many valuable datasets are collected and held by government agencies and organisations and they should ideally be available to researchers. The *Government 2.0 Taskforce Report* recognises that information collected by or for the public sector is a national resource which should be managed for public purposes[25]. *Data.gov.au* is an important initiative that is beginning to address this issue by providing access to public data from both the Australian and state and territory governments[26].

25 www.finance.gov.au/publications/gov20taskforcereport/index.html
26 http://data.gov.au/

This Roadmap includes reference to activities that are being implemented by departments other than DIISR. The inclusion of other portfolios' initiatives in the Roadmap is intended to recognise the breadth of activity in the area and to put research infrastructure capability in its broader context. It does not seek to catalogue all relevant initiatives or expenditure; rather to illustrate the range of interests in this area.

GLOBAL ENVIRONMENT

Increasingly, long-term strategic planning plays an important role in the prioritisation of research infrastructure internationally. A prime example is the European Strategy Forum on Research Infrastructures (ESFRI) 2010 Roadmap[27].

Whilst a national approach is vital, this must be considered in the context of international developments. Australian investment in research infrastructure should not be limited to Australian-based facilities. There must be a high level of global connectivity to ensure Australia maintains international visibility and engagement with global research efforts.

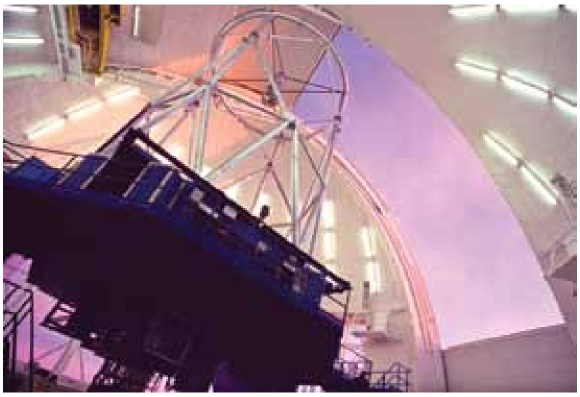


Image C

In some instances, it is more appropriate and cost-effective for Australia to contribute to multinational facilities. There are clear benefits in contributing to an international collaboration to create global infrastructure. Such infrastructure is unlikely to be able to be built by Australia alone and by being part of a global collaboration we ensure Australian researchers are able to access the best facilities in the world.

Another approach is through subscriptions or memberships to allow Australian access to international facilities, data and learned institutes.

NRIC, in its Strategic Framework, advised that research funding programs, as opposed to research infrastructure programs, should consider requests for funding individual Australian researchers' access to overseas facilities.

There is recognition internationally that Australia has cutting-edge research infrastructure facilities across a number of research areas, such as marine observing and phenomics. International research agencies are looking to connect to these networks and are using them as best practice examples. International researchers are often attracted to work in Australia due to the quality of the facilities being provided.

Australia's characteristics, such as its location in the Southern Hemisphere and its unique environment, often provide a competitive advantage for hosting international research infrastructure. These advantages should be capitalised upon, wherever possible, to ensure Australia remains a global player, despite its relatively small size.

It is important to note that there are several drivers and models that should be considered when engaging in international collaborations for the provision of, and access to research infrastructure.

27 http://ec.europa.eu/research/infrastructures/index_en.cfm?pg=esfri

INVESTMENT PRINCIPLES

In parallel with the development of the 2011 Roadmap, NRIC has produced a *Strategic Framework for Research Infrastructure Investment* in consultation with research sector stakeholders[28]. The Strategic Framework can be found at **Appendix A**. The principles set out in the Strategic Framework are intended to guide the development of policy advice and the design of programs at all scales of research infrastructure investment.

This section elaborates on those principles that have specific implications at the national, collaborative level of research infrastructure. The discussion below takes into account the findings of the 2010 NCRIS evaluation[29], which highlighted a number of benefits arising from the approaches taken in implementing NCRIS.

Holistic funding

At the national, collaborative level, the holistic funding principle is of particular importance. This principle recognises that in order to maximise the benefits from research infrastructure investment, funding must be available to support the operation of the infrastructure in addition to capital costs.

Other key elements that require support, as part of research infrastructure funding, include infrastructure project planning, governance, skilled technical support staff, operations and maintenance. It is unrealistic to expect a host institution to cover the operating costs of infrastructure used by a range of institutions, where the infrastructure is essentially being hosted on behalf of the research sector.

Both in feedback to the Roadmap process and in other contexts, the research sector has repeatedly emphasised that human capital is required to deliver efficient and viable research infrastructure facilities. There is an emerging need not only for specialist technical support staff, but also embedded expertise within research teams.

Co-investment

Co-investment is an important consideration when investing in research infrastructure. Any requirements for co-investment should be transparent and as flexible as possible. The NCRIS program, with its flexible approach, delivered co-investment of better than 50 per cent[30].

It is important to ensure there are strong linkages with state and territory governments and industry in order to maximise opportunities for co-investment and encourage a broad user base. In some instances, especially in the case of industry, co-investment can improve networks and strengthen the quality of the research undertaken.

Access and pricing

The access and pricing principle is particularly important for national, collaborative infrastructure as funding is provided to serve a broad range of users, independent of institutional or research group affiliation. Where infrastructure services have a finite capacity and access therefore needs to be rationed, it is vitally important that access and pricing regimes are transparent and facilitate the use of the infrastructure by meritorious researchers. In addition, access to the infrastructure by industry and international researchers should be facilitated through clear policies and processes.

28 www.innovation.gov.au/Science/ResearchInfrastructure/Pages/NRIC.aspx
29 www.innovation.gov.au/Science/ResearchInfrastructure/Pages/NCRIS.aspx
30 www.innovation.gov.au/Science/ResearchInfrastructure/Pages/NCRIS.aspx, pg 79

There are other types of infrastructure, such as data, that if possible should be made available on an open access basis.

There is also a need for research infrastructure providers to ensure a high level of awareness of their services both within and external to the research sector, to encourage access and maximise utilisation.

Prioritisation

As stated above in the Purpose of the 2011 Roadmap section, the determination of priority capability areas is best undertaken through a consultative roadmapping process. In order to ensure a strategic focus and the longevity of this Roadmap, the capability areas identified are described at a high level.

In moving from capability areas to specific investments, it is important that further consultation is undertaken to determine the best location, operating and governance arrangements to support the required research infrastructure. This should include consideration around critical mass, as well as research concentration and collaborations. The consultation should ideally be in the form of a facilitation process, as was used in NCRIS[31].

During the development of this Roadmap, detail has been collected on many specific investments outlined in the submissions, consultations and advice from the EWGs. This material will form an important starting point for any future facilitation process.

An important aspect of facilitation, as identified in the NCRIS Evaluation, is the capacity of facilitators to engage the research community to work together to create investment plans, which optimise resource allocation. The collaborative focus of facilitation can provide a means of bringing together previously isolated members of the research community.

It will be important to include the networks and governance bodies established through NCRIS and the Super Science Initiative as part of this process. It should also involve consideration of how the research infrastructure facilities can be a platform for greater engagement between the research sector and industry.

Due to the move towards a more integrated research infrastructure system, any facilitation process may need to consider a number of capability areas in parallel.

In considering the priorities for specific investment, it will be important to take account of past investments to ensure that high performing facilities that remain a national priority continue to receive support. Preference should be given to maintaining these services, in order to maximise the benefit from the initial investment. In addition, it is important to have mechanisms for dynamically determining the effectiveness of investments during their implementation.

In the case of capability areas identified in the Roadmap but not previously funded, there may be a need to undertake a scoping study to further define the requirements and to understand the ways in which they could be implemented, including in the context of other portfolio and government research and research infrastructure investments.

Excellence in research infrastructure

The way national, collaborative research infrastructure facilities are governed and connected to each other greatly influences their use and impact. There are several governance models currently operating as a result of NCRIS and Super Science investments and more broadly through the research system. It will be important to ensure future governance arrangements

31 http://ncris.innovation.gov.au/development/Pages/default.aspx

benefit from lessons learnt in implementing NCRIS and Super Science. In order to achieve excellence in research infrastructure, it is imperative that cost-effective, efficient and appropriate governance structures and arrangements are utilised and that the governance models employed are focussed on core objectives and are fit for purpose.

It should be noted that the capability areas within the Roadmap do not necessarily equate to single governance entities. There are many aspects to be considered to ensure the most effective governance model is adopted, both within and between capabilities.

RELATED POLICY ISSUES

There are three key aspects of an effective research system: support and funding for research, research infrastructure, and a skilled workforce. It is important that all three areas are considered as part of the overall system and take account of pressures in the various components. There are several important policy issues that relate to research and research infrastructure, but which are beyond the scope of the 2011 Roadmap.

In terms of human capital, the most pressing issue that impacts on research infrastructure is the training and development of skilled staff to provide technical support to the research community. Furthermore, the development of career paths for these skilled staff, particularly moving between academic and technical roles, remains a challenge. During the consultations to develop this Roadmap, there were a number of skill shortages identified, particularly in the areas of statistics, mathematics, taxonomy, informatics and ICT, including computation and simulation science. Without the availability of staff with these skills, it will be a challenge to deliver world-class research infrastructure.

The issue of the potential shortfalls in the supply of research skills in future years was also identified as part of the development work for the Australian Government's recently announced Research Workforce Strategy, *Research Skills for an Innovative Future*[32]. The Strategy found that it was less clear to what extent these shortfalls would impact on individual disciplines and sectors. As part of the implementation of this ten year strategic framework, the government will work collaboratively with research employer groups, professional societies and research training providers to identify and map priority skills needs within individual disciplines and industry sectors over the short, medium and long-terms.

The general level of ICT skills amongst our researchers is another related policy issue. Australia's capacity to deliver internationally competitive research will increasingly rely on developing the skills of all our researchers to operate effectively in an ICT-enabled environment and to make the most of eResearch infrastructure investments. Consultations in the development of the Roadmap have identified a clear need for initiatives to support researchers to upgrade their ICT skills, in particular to manipulate and analyse the ever increasing amounts of data available.

Another important related policy issue is how to foster increased collaboration between industry and research organisations. For example, the *2011 Australian Innovation System Report* indicates that in 2008-09 only 2.4 per cent of innovation-active businesses collaborated with universities or other higher education institutions[33]. There are broad policy initiatives through the Innovation Agenda that are seeking to improve collaboration between researchers and industry in order to assist in translating research outcomes into increased productivity. Improving industry access to research infrastructure is one mechanism that can support this goal.

32 www.innovation.gov.au/Research/ResearchWorkforceIssues/Documents/ResearchSkillsforanInnovativeFuture.pdf
33 www.innovation.gov.au/Innovation/Policy/Pages/AustralianInnovationSystemReport2011.aspx, pg 84

CAPABILITY AREAS

INTERACTIONS BETWEEN RESEARCH PRIORITIES AND THE CAPABILITY AREAS

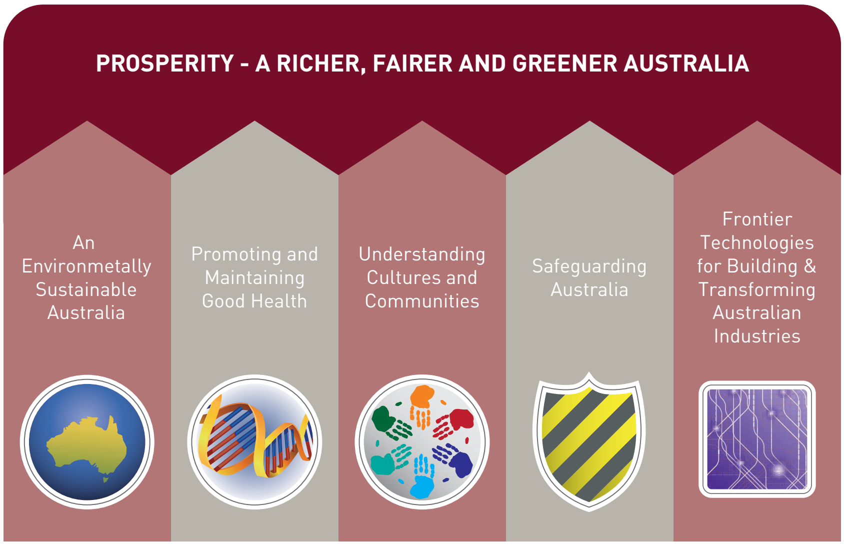
The 2011 Roadmap outlines research infrastructure capability areas required to support excellent research across priority areas. The outcomes from this research will contribute to economic development, social wellbeing, environmental sustainability and ultimately Australia's prosperity.

The capability areas described in the 2011 Roadmap were identified through a broad consultative process, which sought input directly from researchers and other stakeholders regarding future research directions and research infrastructure requirements at the national, collaborative scale.

These capability areas contribute in a multitude of ways to Australia's National Research Priorities (NRPs)[34]. The NRPs reflect areas of particular importance to Australia in which a focussed research effort has the potential to improve broader policy outcomes and drive national prosperity.

In addition to the four NRPs, the 2011 Roadmap includes an additional area, reflecting the importance of research into understanding cultures and communities.

Figure 2 – Diagram of research priorities



Most of the capability areas identified in the 2011 Roadmap clearly support research across more than one research priority, which demonstrates the benefits of a national, collaborative approach to research infrastructure investment. In addition, it highlights the complex interactions between capability areas, which are needed to deliver comprehensive and effective research infrastructure to solve research problems.

34 www.innovation.gov.au/AboutUs/KeyPublications/Documents/InnovationPortfolioFactSheets.pdf, pg 144

Table 1 is intended to illustrate the ways in which various capability areas could contribute to a specific research priority. It should not be read as an indication of the relative priorities of the individual capability areas.

To highlight the research priorities to which each capability area contributes, graphical icons (as shown in Figure 2 and Table 1), representing each of the NRPs and Understanding Cultures and Communities, have been included with the title of each capability area.

Table 1 – Illustration of the capability areas' relationship to research priorities

	An Environmentally Sustainable Australia	Promoting and Maintaining Good Health	Understanding Cultures and Communities	Safeguarding Australia	Frontier Technologies for Building & Transforming Australian Industries
Research Outcome Targeted Capability Areas					
Marine Environment	✓			✓	
Terrestrial Systems	✓			✓	
Atmospheric Observations	✓	✓			
Solid Earth	✓			✓	✓
Urban Settlements	✓	✓	✓	✓	
Sustainable Energy	✓				✓
Integrated Biosecurity	✓	✓		✓	
Cyber Security				✓	✓
Astronomy					✓
Population Health Research Platforms		✓	✓	✓	
Translating Health Research		✓			✓
Cultures and Communities	✓	✓	✓	✓	✓
Enabling Capability Areas					
Integrated Biological Discovery	✓	✓		✓	✓
Biological Collections and Biobanks	✓	✓		✓	
Characterisation	✓	✓	✓	✓	✓
Fabrication	✓	✓		✓	✓
Space Science	✓			✓	✓
Digitisation Infrastructure	✓	✓	✓	✓	✓
eResearch Infrastructure	✓	✓	✓	✓	✓

CAPABILITY AREA GROUPINGS

As discussed in earlier sections, the research environment is becoming increasingly interlinked and as such, the research infrastructure required to address research questions becomes more complex.

There is a challenge in separating highly inter-related and overlapping research infrastructure needs into discrete capability areas. It should be recognised that the greatest efficiency and outcomes will be achieved if the capability areas are not implemented in isolation.

A number of capability areas are clearly research outcome targeted, for example, the Marine Environment capability area. While the focus of these capability areas may be on a particular research outcome, the complex nature of answering today's research questions requires linkages, interaction and collaboration with many other areas.

Other capability areas enable research across a breadth of disciplines and also support the outcome targeted capability areas. For example, eResearch infrastructure is a pervasive and underpinning requirement, as is capability in the 'omics. The overarching ICT needs for the capabilities were considered during the consultation process and are captured within the eResearch Infrastructure capability area.

While the capability areas have been separated into these two categories to assist in articulating the critical linkages and relationships between them, it is important to note that there is a continuum between research outcome targeted and enabling capability areas. There are instances where research outcome targeted capability areas are enabling for other targeted capabilities. For example, the data collected through the Terrestrial Systems and the Marine Environment capability areas will be important inputs into Integrated Biosecurity.

It should be noted the capability areas described in this Roadmap are not necessarily of the same scale, and the order they appear in the Roadmap is not indicative of relative priority. The order represents an attempt to group the capabilities along thematic lines. This is not definitive but indicates some of the linkages within the broader groupings.

Need for an integrated approach

Complex research problems will require the use of research infrastructure from an array of capabilities. In order to illustrate this further, the Roadmap includes a number of examples of cross-cutting issues that will require significant collaboration among research infrastructure facilities. These are identified in the Roadmap as examples describing key areas that require an integrated approach and include: Climate and Carbon (page 29), Coastal Systems (page 38), Sensors and Instrumentation (page 73) and Computational Science (page 89). These examples provide a useful lens through which to consider prioritising specific future investments within individual capability areas.

RESEARCH OUTCOME TARGETED CAPABILITY AREAS

The capability areas under this heading can be viewed as discrete areas, however the greatest impact will be achieved if they work together, particularly if they do so with a focus on national and global challenges.

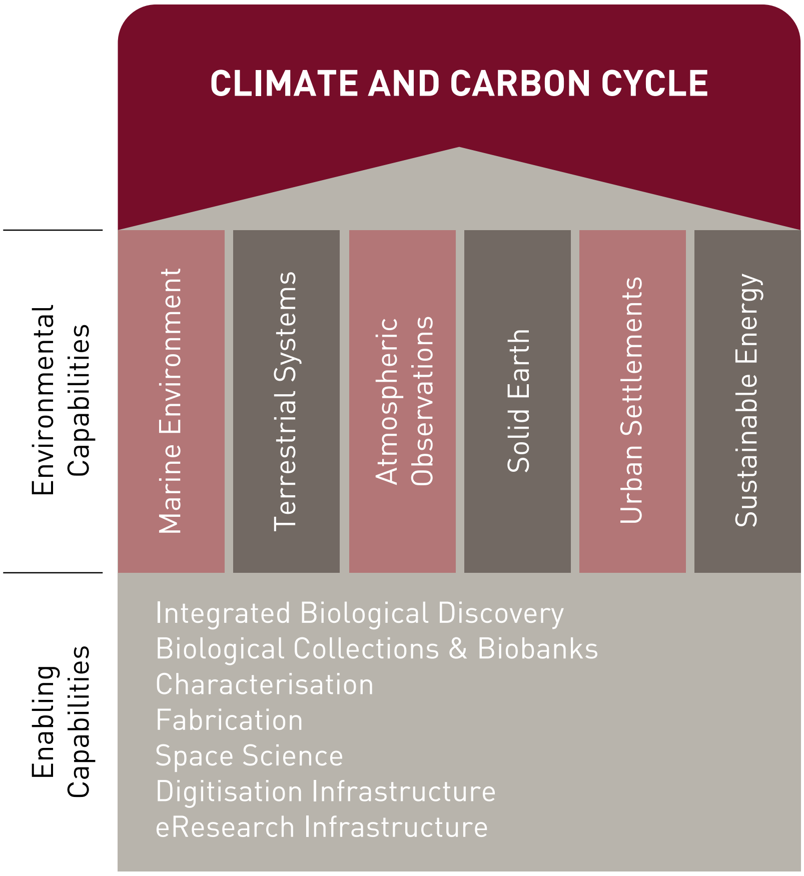
National and global challenges such as food, water, resource and biological security; the impacts of increasing human population and health costs; and adapting to climate change continue to be high priority drivers for innovation and research in Australia.

The inter-relatedness and complexity of these challenges increasingly demands a systems approach to research and the development of research capability, including infrastructure, human capability and collaboration networks, both nationally and internationally.

For example, while the Roadmap has divided the natural environment into discrete, domain specific areas, they may also be considered as a set of environmental capabilities that enable systems level research into our natural, managed and urban environments.

One instance of how the cross-cutting linkages and dependencies between capabilities may contribute towards addressing a specific challenge is depicted in Figure 3.

Figure 3 – Example of cross-cutting linkages and dependencies



MARINE ENVIRONMENT

DESCRIPTION

Australia is a marine nation, extending from the tropics through subtropical and temperate waters down to the Antarctic continent, and its future is linked to its oceans.

Planning for the future, whether for adaptation to climate change or the management of marine resources, requires access to the best possible ocean information. Sustained observations of the ocean are essential to deliver the knowledge needed to inform decisions made by government, industry and the community.

The Marine Environment capability will continue to require an integrated and coordinated approach to data collection, storage and management. Modelling and interpretation of this data will support a greater understanding of the marine environment, including coastal ecosystems and marine resources.

STRATEGIC IMPACT

The scope of research in the marine environment is extensive. Australia needs to continue to capture the benefits of its growing marine capability, to expand its coverage and to sustain it in the long term. In addition, the maintenance of an ongoing, robust national framework for planning and coordination between marine science agencies and the wider marine community remains vital.

Recently released national frameworks and plans for climate[35], marine[36], the Antarctic[37] and Earth system science[38] provide important guidance and linkages for strategic marine research infrastructure investment.

Sustained observations in the global ocean and the oceanic regions surrounding Australia are critical to detecting and attributing climate change and improving projections of changes and their impacts. Research infrastructure in these areas will support a strong blue water and climate science program that addresses priorities identified in the *National Framework for Climate Change Science*[39].

Enhanced capability in marine observation is equally important for the sustainable management of the marine environment, including the use of biological and seabed resources and the protection of ecosystems that are under threat from human influences. Australia's marine industries, national security and maritime safety also depend on knowledge of our oceans. By enhancing Australia's marine research capability we can advance our understanding of coasts, climate and carbon cycles.

35 www.climatechange.gov.au/government/initiatives/~/media/publications/science/national-framework-cc-science.ashx
36 www.opsag.org/pdf/opsag-marine-nation-01.pdf
37 www.antarctica.gov.au/science/australian-antarctic-science-strategic-plan-201112-202021
38 www.science.org.au/natcoms/nc-ess/documents/ess-report2010.pdf
39 www.climatechange.gov.au/government/initiatives/national-framework-science

CHALLENGES AND ASSUMPTIONS

Image D

An integrated and coordinated approach to marine observing provides powerful support for the research required to understand and manage our marine environment. A long-term commitment with supporting infrastructure is required to sustain and enhance research efforts. There is an increasingly important need to integrate marine observations across all of Australia's ocean territory, with emphasis on the discoverability, accessibility and interoperability of associated data streams.

A specific challenge for the Marine Environment capability area is the coordination of activities with other related national collaborative infrastructure to advance scientific cooperation and the sharing of hardware, platforms, modelling, and data and information capabilities. The focus for this cooperation should be to achieve scientific outcomes that improve knowledge and understanding of key issues for lands, coasts, oceans, climate and the carbon cycle.

Increasing effective engagement with, and leverage of, international marine science initiatives under the framework of the *Global Ocean Observing System*[40] is key to strengthening Australia's marine research capacity and research outcomes. Securing ongoing and long-term support for participation in these initiatives will provide substantial returns for Australia's efforts.

Management of the vast natural resources of our marine environment depends on understanding our marine biodiversity and the structure and function of our marine ecosystems. This requires knowledge of Australia's biodiversity, including the identity of organisms, their genetic diversity, the relationships between organisms, and their functional role in ecosystems. In this context, a significant challenge is to develop innovative rapid assessment technologies for living systems in the marine environment. Strong linkages to the Integrated Biological Discovery and Biological Collections and Biobanks capability areas will be required.

The Australian region, and indeed the Southern Hemisphere, suffers from a paucity of palaeoclimate records, including marine records, and greater effort is required to expand and synthesise these records into regional, hemispheric and global reconstructions of climate. Maintaining and building Australia's capability in palaeoclimate research is an important contribution to global climate science.

40 www.ioc-goos.org

Linkages to the Space Science capability area are important as satellite-based remote sensing capabilities are crucial to ocean, climate and cryospheric research efforts. The continued development of advanced sensors and sensor networks is also an underpinning requirement.

The integration of terrestrial and marine observations is required to better understand Australia's vast coastal domains. There is a critical need to identify a fundamental set of observations and data for this purpose. Conducting and coordinating research in the coastal zone represents a significant challenge given the complexity of working across disciplines, communities, jurisdictions and interests.

In addition, strong connections need to be developed between this capability and the Atmospheric Observations capability to ensure research into the complex ocean and atmosphere interactions can be most effectively supported.

SPECIFIC REQUIREMENTS

Investment in ocean observation should be continued as the existing investments have achieved significant and internationally recognised benefits. The coverage should be extended to fill significant gaps in current observations. Consideration should be given to including areas such as the deep ocean, the coastal oceans, the seabed, the under sea-ice environment, the Antarctic cryosphere and the oceanic regions surrounding Australia.

It is also important to ensure that progress in establishing the Australian Ocean Data Network (AODN) is sustained long-term, so that governments, industry and communities derive maximum value from all investments made in gathering ocean information.

Other key infrastructure needs include the continued support for blue water research capacity to ensure the benefits of the recent Landmark scale investment into the Marine National Facility is maximised. In addition, maintaining the existing capacity for tropical experimental research is a priority. A marine experimental research capability to support temperate and cold water experimental science could also be considered.

Access to coastal and ice-breaking marine science capabilities is also important, but any investments in new vessels are likely to be at a Landmark scale and part of considerations broader than research and as such do not fall within the scope of the Roadmap.

Linkages to molecular biology technologies and tools including the 'omics to support marine observations capability are required, especially in the area of ecosystem metagenomics. This will support an increased understanding of marine biodiversity and ecosystem dynamics.

Sustained investment is required in the human and physical infrastructure needed to develop enhanced data management and analysis tools, in collaboration with the eResearch Infrastructure capability, to improve integration across observations, characterisation and modelling, and to increase uptake by end users including researchers and policy makers.

There is an additional need for sustained support that enables Australian participation in major international ocean science programs.

TERRESTRIAL SYSTEMS

DESCRIPTION

The millennium drought, food price spikes and recent extreme weather and climate events have focused attention on the issues of climate variability and changes in terrestrial systems. Investment in research infrastructure capability for terrestrial systems requires an integrated and interdisciplinary view due to the complex and inter-related nature of the systems themselves.

A collaborative and integrated research capability is required with observation and surveillance infrastructure coupled with data-intensive analytical techniques. More specifically, the research infrastructure capability should provide a foundation for research into how ecosystems are structured and function, the role they play in providing resources and how they can be managed sustainably.

STRATEGIC IMPACT

Pressing national and global environmental challenges continue to be strong drivers for innovation and research in Australia. Such challenges include addressing food, water, resource and biological security; dealing with the impacts of increasing human population; adapting to climate change; and the reduction of greenhouse gas emissions.

Strengthening our understanding of terrestrial systems is vital to the health and sustainability of Australia's environment. A national view of the status and evolution of ecosystems in both natural and managed landscapes within the global context is required. Primary threatening processes that need to be understood include various forms of land degradation, salinity, natural hazards (including floods and cyclones), scarcity of freshwater resources, loss of biodiversity and climate change. These processes are exacerbated by increasing urbanisation, particularly in the coastal zone.

Long-term observation and experimentation in agricultural and forest systems is essential for understanding terrestrial biogeochemical cycles and the environmental impacts of agriculture and forestry. Investment in this area will bring a renewed focus on Australian soils to address important research questions, such as the potential for carbon sequestration and the sustainability of managed landscapes.

CHALLENGES AND ASSUMPTIONS

Image E

It is recognised that improving the integration of data relating to Australia's terrestrial systems is a big task. The degree of difficulty derives firstly from the complexities of the systems being studied and secondly from the range of researchers, organisations and jurisdictions involved in environmental research and management.

Linkages across the environmental capabilities through shared approaches to information management infrastructure should continue to be strengthened. For instance, collaborative development of integrated observing and information systems for the coastal zone will be important for this critical area. eResearch infrastructure provides an enabling platform for data-intensive capabilities across the environmental domain.

In order to improve our understanding of Australia's biodiversity, this capability area will need to interact with and link to the Integrated Biological Discovery and Biological Collections and Biobanks capability areas. This will ensure Australia develops capacity in ecosystem metagenomics as a logical adjunct to the establishment and expansion of terrestrial and marine ecosystem observations. In particular, this will increase our understanding of the genetic diversity and genomic profile of organisms, the relationships between organisms and their functional role in ecosystems.

There are also important linkages with the Integrated Biosecurity capability area, for example in order to understand biodiversity responses to changes in abundance and distribution of pests and diseases.

In addition, this capability area needs to interact with the Space Science capability regarding remote sensing. It also relies on the continued development of advanced sensors and sensor networks.

Investment should be coordinated with key initiatives such as the *National Plan for Environmental Information*[41], the Bureau of Meteorology's *Australian Water Resources Information System*[42] and state government programs (such as the Goyder Institute in South Australia).

41 www.environment.gov.au/npei/index.html
42 www.bom.gov.au/water/about/wip/awris.shtml

SPECIFIC REQUIREMENTS

Investments to date represent a good start in establishing the necessary long-term observing and information systems for terrestrial systems research. While maintaining and strengthening existing capacity, there is a need to extend the coverage across a range of ecosystems and to improve integration.

Key infrastructure needs include:

- extension of the network of baseline sites, 'super sites' and long-term ecological research sites to include aquatic ecosystems, the coastal zone and managed landscapes, with agreed measurement protocols
- observing systems to monitor soil condition to enable research into soil carbon sequestration as well as spatial distribution of soils and changes over time, including water storage, carbon dynamics and nutrient availability
- standardisation of methods for measurement and analysis (for example those relating to the carbon cycle)
- improved capacity for measurement and monitoring of freshwater ecosystems and biodiversity with increased focus on the function, resilience and response of aquatic ecosystems, including experimental research infrastructure at the ecosystem scale
- provision of enhanced fit-for-purpose models and predictive capabilities
- sensor technologies and networks for improved and coherent measurement of parameters in priority ecosystems
- support for the emerging techniques of environmental metagenomics
- shared approaches to data management and ICT infrastructure to support discovery, access and interoperability of datasets, and national coordination in areas such as developing metadata standards.

ATMOSPHERIC OBSERVATIONS

DESCRIPTION

The atmosphere is a critical component of the environment in which we live and changes in its state impact the daily lives of Australians. Atmospheric circulation systems connect key regions of the world, interacting with processes in the ocean, over ice and on land.

An atmospheric observations capability is required to support the research activities that build our ability to monitor and understand atmospheric processes, particularly for climate research activities and the prediction and monitoring of high impact weather. This capability will involve an observing network, both *in situ* and remotely-based, to monitor atmospheric state and composition, atmospheric evolution, and clouds and rainfall.

STRATEGIC IMPACT

Atmospheric observations are routinely undertaken by both operational and research agencies. Through optimising and expanding Australia's ability to utilise this data by the whole atmospheric research community, significant gaps in measurements of greenhouse and reactive gases, clouds and aerosols can be addressed. This will increase our ability to predict atmospheric behaviour and improve our understanding of how the atmospheric component of the climate system behaves. This capability is central to the *National Framework for Australian Climate Change Science*[43].

Increasing concentrations of greenhouse gases (GHGs) and changing aerosol concentrations are driving significant changes in global and regional climate. Regional differences in the concentrations and isotopic composition of GHGs can be used to infer the spatial and temporal variability in their sources and sinks and thus to inform mitigation strategies. Knowledge of the sources and sinks of GHGs is fundamental to projections of climate change and are important in international negotiations in the United Nations' *Framework Convention on Climate Change*[44].

Potential changes in rainfall are one of the most critical issues facing Australia. Rainfall patterns are controlled by large scale atmospheric circulation, internal modes of variability and local and regional processes, including cloud processes. The simulation of circulation features in climate models critically depends on the accurate depiction of cloud and aerosol processes. Thus, major uncertainties in cloud and aerosol processes affect rainfall prediction across the country and new observational programs on regional cloud processes, aerosol concentrations, their interactions and representation in models will lead to substantial further progress.

Regular high quality cloud and aerosol measurements will enable Australian research to contribute to the global understanding of cloud effects and feedbacks as well as direct and indirect aerosol radiative effects. Australia is well placed to lead long-term cloud and radiation measurement sites in the tropics and high latitude/polar regions of the Southern Hemisphere.

43 www.climatechange.gov.au/government/initiatives/national-framework-science.aspx
44 http://unfccc.int/essential_background/convention/background/items/2853.php

CHALLENGES AND ASSUMPTIONS

The capability required to advance the most critical issues in this area requires comprehensive atmospheric measurements of a set of interconnected parameters, ranging from GHGs to aerosols, from reactive gases to cloud properties, and the associated rainfall distribution at a range of sites. Some important components of the required observational sites already exist through national and international investments. The opportunity is to build on the existing capacity to provide the comprehensive measurements, including strong linkages with the relevant parts of the Marine Environment and Terrestrial Systems capability areas.

There are three existing measurement sites, each covering part of the required comprehensive measurement capabilities, which can be leveraged for the proposed enhancement: the Cape Grim Baseline Air Pollution Station (operated by the Bureau of Meteorology), the Darwin Climate Research Station and the Brisbane Radar Facility. Completing measurement capabilities over land at these three sites will advance many of the issues highlighted above. Due to the vast and difficult to access Southern Ocean, increasing our knowledge of clouds and their interaction with aerosols will continue to be a challenge, but this knowledge is needed to reduce uncertainties in climate forecasts.

Remote sensing technologies such as satellites are starting to be used in estimating the emissions, transport and chemistry of trace gases and aerosols from large scale diffuse sources, for example from fires and wind blown dust. Ground-truthing is an essential step in order to make effective use of these products over the Australian landscape. This relies on high quality *in situ* observations of trace gases and aerosol chemical components and size distributions. A key challenge is the setting of a national protocol for the measurement of fine particles.

The quality and quantity of satellite data on many aspects of the atmosphere have increased dramatically in recent years. This data is particularly important in the sparsely observed Southern Hemisphere and today many parameters can be measured globally from satellites. However, Australian investment in the exploitation of this data through its analysis, verification and integration with *in situ* data and its assimilation into models has not kept pace with the increased international capability. Access to these increasingly important data streams and their exploitation for Australia's benefit requires strong participation in both international and national programs to exploit both the observations and their use in modelling[45]. These requirements are discussed further in the Space Science capability area.

It will be important to ensure that approaches to data management and eResearch infrastructure are considered in collaboration with the other environmental capabilities in particular, to facilitate improved understanding of key issues, such as climate and the carbon cycle.

45 www.science.org.au/reports/documents/EOSfinal.pdf

SPECIFIC REQUIREMENTS

Addressing these major opportunities and challenges requires an atmospheric composition observing network that would combine *in situ* and remote sensing infrastructure and document trends in reactively and radiatively important gases, aerosol concentrations, solar and terrestrial radiation, as well as cloud and precipitation structures.

For estimation of the regional sources and sinks of GHGs, high quality stations such as Cape Grim need to be supplemented by higher spatial resolution concentration measurements of GHGs, as well as surface fluxes of carbon dioxide. Also, future satellites' measurements, when combined with measurements like those provided by the high quality stations and the network proposed here, will result in a step change of the scientific capability to infer national and regional GHG sources and sinks.

Therefore, consideration should be given to a network of *in situ* automated GHG and aerosol observing stations and radiation measurements, co-located with existing weather and/or flux tower networks.

A smaller but mobile version of these key observing systems is technically feasible and would support research in the important Southern Ocean region through deployment on islands (for example, Macquarie Island) or ships (for example, the Marine National Facility and the *Aurora Australis*). Mobile capability would also enable researchers to focus on key source and sink processes such as carbon capture and storage in the major coal/gas basins.

There is also a requirement for improved ability to utilise satellite data directly and in Earth system modelling to underpin a wide range of climate and environmental research activities. This would need strong participation in international satellite programs, verification and calibration activity, and infrastructure to collect, process, interpret and distribute the resulting information.

In addition, enabling infrastructure in data analysis and modelling will be vital to maximise the outcomes from this capability area.

EXAMPLE

CLIMATE AND CARBON - NEED FOR AN INTEGRATED APPROACH

Australia, as a nation extending from the tropics to Antarctica, is strongly influenced by global and regional climate variability and change. This results from interactions between all elements of the climate system on local, regional and global scales. Increasingly, human activities are interacting with this natural variability and driving further global change.

Prediction of inter-annual climate variability, Australia's drought-flood cycle and projections of longer term climate change, including changes in climate phenomena and the intensity and frequency of extreme events, require a sound understanding of climate system science and the development of robust models. Climate change science will continue to be essential in supporting the three pillars of the Australian Government's climate change policy: action to reduce greenhouse gas emissions, action to adapt to climate change that we cannot avoid, and action to help shape a global solution.

Sound, long-term observational data across all of the Earth's natural domains is critical to providing robust predictions of future climate and the impacts on the natural and built environment. Most critical are the storage and fluxes of heat, water and carbon and other radiatively-active gases within and between the atmosphere, ocean, terrestrial environment and the cryosphere. These observations need to include in situ observations, satellite observations, data archaeology (the recovery and digitisation of historical records) and paleoclimate records.

The integration of observations from the many data streams is critical to fully understand the cycling of heat, water and carbon and their interactions and impacts with the natural and built environment. In order to investigate these pressing issues, the environmental capabilities outlined in this Roadmap, including Marine Environment, Terrestrial Systems, Atmospheric Observations, Solid Earth and Urban Settlements, must work together to provide high quality, interoperable, accessible, discoverable and model ready data streams. These capabilities must also forge links with key initiatives at both the national and state level, such as the National Plan for Environmental Information[46].

In addition, key underpinning eResearch infrastructure is required to provide data systems that can be used efficiently and effectively for domain specific studies and broader integrative modelling. The other enabling capabilities outlined in this Roadmap are also essential to provide support for this integrated approach.

46 www.environment.gov.au/npei/index.html

SOLID EARTH

DESCRIPTION

Image F

The Earth's crust provides many crucial services essential to the wealth and health of society. It is the platform on which we live, it provides the mineral, energy and groundwater resources on which we depend and it increasingly serves as a repository for our hazardous wastes. It contains a precious archive of past climates and the history of life. It is also the source of some of the most catastrophic natural hazards faced by the world.

Accurate information about the Earth's lithosphere (comprising the crust and underlying mantle) supports both our understanding of the fundamental geological processes and structures, and the manner in which they evolved over time.

Infrastructure is required to allow for the acquisition and study of properties of the Earth's structures and materials, access and interoperability of large and complex datasets, along with software tools for simulation and modelling.

STRATEGIC IMPACT

With the collective scale of human activity now rivalling many natural geophysical processes, the Earth sciences are providing the framework for understanding how we impact on the functioning of our planet and the sustainability of its resources.

Humanity's relationship with the Earth is complex. Natural hazards are driven by the underlying crustal stress regime and other Earth properties. These in turn influence the distribution of mineralisation, energy and the capac ity to store waste including carbon dioxide. Improved understanding of the Earth's lithosphere will allow us to better use its resources in a sustainable manner.

Earth sciences contribute to:

- advancing our understanding of climate change, through understanding past climate patterns and identifying and assessing opportunities for reducing adverse impacts
- supporting the discovery and cost-effective, sustainable use of minerals and energy resources
- characterising the extent and nature of Australia's groundwater resources to improve our understanding and the potential for their increased use in a period of climatic uncertainty
- providing understanding and early warning of natural hazards such as earthquakes and tsunamis
- supporting coastal zone research by accurately defining vertical and horizontal position, and by describing the nature and erosion or advance of the coastline.

There is a need to build on existing investments to ensure that the Australian continent remains one of the most integrated and instrumented continental observing platforms on Earth. Extending the nation's expertise to the surrounding deep ocean floors and the deepest levels of the accessible lithosphere will enhance our ability to resolve its physical state. This research will improve our understanding of how the crust will respond to interventions, such as geothermal energy production, carbon dioxide storage, isolation of dangerous wastes and earthquake hazards.

CHALLENGES AND ASSUMPTIONS

Previous investment has facilitated the implementation of an integrated infrastructure system for Earth science by deploying a range of capabilities in data acquisition, management, modelling and simulation across the geospatial and geoscience spectrum. A future challenge will be to create a fully integrated Earth observatory.

Considerable effort is being devoted by the geoscience community to the development of capabilities for managing and sharing large datasets and the tools to analyse data and develop models. Significant potential exists for the wider application and development of these capabilities across other research areas.

In order to address these challenges, this capability area will need to have strong linkages to the Space Science, Sustainable Energy, Characterisation, Digitisation Infrastructure and the other environmental capabilities. It is also reliant on continued development of advanced sensors and sensor networks.

SPECIFIC REQUIREMENTS

Further support for the existing investments will maintain Australia's world-leading abilities in this area and sustain the collaborative behaviours of this community. Sustained and enhanced data acquisition, data management, analysis, modelling and simulation capabilities, building on those being implemented through current investments, are also needed. In addition, support for new data streams will be required.

In order to support the development of this capability area, additional capacity should be considered in:

- Earth imaging to provide an equipment pool deployable to enable greater coverage and additional geophysical data across large areas of Australia, including the ocean floor as well as increased acquisition of reflection transects
- geospatial systems (including both physical and eResearch infrastructure), to improve accuracy and time resolution for geoscience and other research areas that require spatial data
- Earth model construction to allow simulation codes to interoperate with e-Earth infrastructure
- an observatory of the subsurface of the Earth that allows researchers access to instrument, log and monitor for a variety of purposes including geothermal energy, mineral systems, paleoclimatology, groundwater and carbon dioxide storage
- dedicated ICT, in particular data storage and software engineering support to achieve the transition of virtual libraries to virtual laboratories
- geochemical instruments, including a synchrotron beam line suitable for Earth science research.

URBAN SETTLEMENTS

DESCRIPTION

Understanding of the physical, social, economic and ecological aspects of urban settlements is essential to improve the environmental sustainability of cities and other urban areas, and in improving economic prosperity and quality of life.

The Urban Settlements capability will require facilities that enable the collection and integration of datasets covering the range of human activities by those working, investing and living in urban areas. The capacity to understand the physical and social aspects of urban settlements, as well as acquiring an understanding of the management of the interactions between people and their urban environments is required to solve a myriad of future research challenges.

STRATEGIC IMPACT

While urban settlements range from cities and smaller urban areas to households, a few major urban settlements host the vast proportion of the Australian population and a similar share of the nation's production and consumption, economic activity and social interaction. Parts of regional Australia are undergoing considerable economic change which will present social and environmental challenges to urban settlement over coming decades. The long-term environmental, social and economic sustainability of Australia's urban settlements will define the lived experience of the population, its environmental impact and its economic prosperity.

Difficult issues of resource consumption (including energy and water), waste production (including greenhouse gases), transport, food security, liveability, housing, employment and economic activity, urban concentrations on the coast, health and wellbeing are being faced in all major Australian settlements.

To understand urban settlements from research, policy, management and design perspectives, it is essential to have reliable and nationally consistent data in which settlements can be described as systems. That is, both as physical sites whose systems may be the subject of scientific analysis, and as social and economic sites in which human behaviours, production and consumption occur that themselves have consequences for environmental, social and economic sustainability.

CHALLENGES AND ASSUMPTIONS

Understanding and managing the complexity of modern cities is impossible without strong cross-disciplinary approaches which span the natural and social sciences and the humanities and are enabled by eResearch infrastructure.

Relevant datasets cover demographics, resource consumption, transport, housing, space usage, socio-economic status and activities, and wellbeing. Integrating these datasets demands engagement with multiple public and private sector interests that hold the data and utilise research outcomes, and with a wide range of disciplines interacting within a broadly defined urban studies field. Coordination of data capacities and infrastructure will be vital.

An effective capability in this area would interact and link with many other capability areas, including the range of health and environmental capabilities as well as the Sustainable Energy, Integrated Biosecurity, and Cultures and Communities capability areas. For example, collaboration with the Solid Earth capability area will enhance our understanding of the vulnerability of communities to the impact of natural hazards.

SPECIFIC REQUIREMENTS

Recent investment in this area represents the first substantive attempt to organise data into an integrated research infrastructure for urban research. As this investment matures, there will be a need to develop further areas of focus, to attend to emerging gaps and consider extension for greater national coverage.

In addition, infrastructure is required to address outstanding issues of national consistency and interoperability across data sources, such as geo-coding and other adjustments to routinely collected data that will enhance access for research use.

There is also a need to support the ongoing maintenance of and access to critical data across national, metropolitan and local scales which is held by a wide range of organisations and agencies. Improved coordination will better support the coherence and excellence of urban research in Australia.

Investment is needed in facilities for modelling social and environmental interactions and this must involve linkages to the environmental capabilities outlined in this Roadmap. Furthermore, the capacity for visualisation needs to be incorporated.

SUSTAINABLE ENERGY

DESCRIPTION

Australia's prosperity relies on secure, affordable and sustainable energy. The Australian Government has legislated for 20 per cent of electricity to come from renewable energy by 2020 and a reduction in our greenhouse emissions by 80 per cent over the next 40 years[47]. To achieve these goals, current investments in maturing existing technologies need to be complemented by infrastructure that enables research into next generation or disruptive technologies.

A coherent energy system will require a mix of technologies. This may include uptake of clean coal technologies to reduce greenhouse gas emissions, supported by increasing adoption of sustainable sources of energy, and complemented by technologies that address carbon sequestration as well as energy conversion, efficiency, storage and distribution.

Australia has access to a number of significant sustainable energy sources that are beginning to contribute to energy generation, including solar and wind, with geothermal and ocean power as potential future sources. Next generation biofuels, battery and fuel cell technologies are some of the energy options under development for transport and field use. A long-term solution for large scale, non-polluting energy supply may eventually come from nuclear fusion. The future energy landscape will undoubtedly be more diverse than the present one.

STRATEGIC IMPACT

Image G

Providing secure, affordable and sustainable energy is vital to maintaining Australia's prosperity. Demand for Australia's energy, both domestically and for export, is growing strongly. We must ensure that our energy resources are developed efficiently and sustainably to optimise the overall benefit for the Australian community.

Continued security of, and access to, a competitively priced energy supply for households and industry is critical. At the same time, Australia needs to continue the transition to a low emission, environmentally sustainable economy. This will require the development and deployment of new and cleaner low emission technologies supported through actions such as the introduction of a price on carbon. It will also require additional, targeted government support for those clean energy innovation processes that offer significant future abatement potential for Australia.

47 www.cleanenergyfuture.gov.au/

Advances in energy systems engineering fundamentally rely on the discovery of advanced materials, their fabrication into components and deployment in engineered systems. There is clear potential for disruptive technologies in energy systems, affecting sectors such as energy generation, hydrocarbon exploration and exploitation, vehicle technology and electrical power networks.

To capture a portion of the high value growth markets arising from such developments, Australia will require infrastructure that supports research along the value chain from materials design to component prototyping and testing.

Advancing the understanding of Australia's energy system and the potential impact of emerging technologies on the production, distribution and consumption of energy will be crucial to informing policy that drives appropriate infrastructure and other investment choices.

CHALLENGES AND ASSUMPTIONS

There are a range of activities being undertaken to address energy and emission issues relevant to a sustainable energy landscape. These include the recently announced *Clean Energy Future*[48] plan, which outlines a number of initiatives that will drive investment in research infrastructure to support research into clean energy sources. In particular, the Australian Renewable Energy Agency (ARENA), the Clean Energy Finance Corporation and the Clean Energy Innovation Program[49] are likely to drive expansion in this area.

ARENA will administer the $3.2 billion in Australian Government support for research and development, demonstration and commercialisation of renewable energy technologies, including a number of current renewable energy initiatives, for example:

- the *Solar Flagships Program*[50], which supports the construction and demonstration of large scale, grid connected solar power stations in Australia
- the *Australian Solar Institute*[51], established by the Australian Government to support solar thermal and solar photovoltaic research and development
- the *Australian Centre for Renewable Energy*[52], which promotes the development, commercialisation and deployment of renewable technologies through a commercial investment approach
- the *Australian Biofuels Research Institute*[53], which will aim to increase Australia's energy security and diversify sources of liquid fuel supply through the next generation biofuels.

48 www.cleanenergyfuture.gov.au/
49 www.innovation.gov.au/Industry/CleanEnergyFuture/Pages/default.aspx
50 www.ret.gov.au/energy/clean/cei/sfp/Pages/sfp.aspx
51 www.ret.gov.au/energy/clean/cei/asi/Pages/default.aspx
52 www.ret.gov.au/energy/clean/cei/acre/Pages/default.aspx
53 http://minister.ret.gov.au/mediacentre/mediareleases/pages/budgetaustralianbiofuelsresearchinstitute.aspx

There is also a range of other programs that complement the Clean Energy Future Plan as part of the broad ongoing effort to support clean energy innovation, including:

- the *Energy Transformed Flagship*[54], which aims to provide sustainable, efficient, cost-effective energy solutions
- the *Carbon Capture and Storage Flagships Program*[55], which supports the construction and demonstration of large scale integrated carbon capture and storage projects in Australia
- the *Smart Grid, Smart City*[56] project, which will demonstrate a range of smart grid technologies and applications, providing extensive data about the potential benefits.

A major challenge will be to ensure any investment in research infrastructure complements these various research and demonstration efforts and provides a basis for further fundamental research.

The Energy White Paper process being undertaken by the Department of Resources, Energy and Tourism, expected to be finalised in 2012, should also inform future consideration of the infrastructure requirements for energy research.

The existing investments and any future enhancements in the Characterisation and Fabrication capabilities should provide significant fundamental support for energy research, particularly in the advanced materials area. In addition, the subsurface observation capacity proposed in the Solid Earth capability area has clear applicability to research into carbon capture and storage and geothermal energy.

SPECIFIC REQUIREMENTS

The broad nature and scale of energy related research and development means that infrastructure to support research into specific processes and related activities ranges from laboratory scale equipment to pre-pilot facilities capable of scaling-up processes, through to larger demonstration or prototype facilities that may lead to commercial and industrial development.

A strategic approach will be required to develop a coordinated whole of government understanding of the type and level of investment in infrastructure necessary to support sustainable energy research and development across both fossil and renewable energy sources. This should take into account the current policy framework, existing and planned investments and initiatives, areas of research strength and the international energy research environment.

The focus of investment in national, collaborative research infrastructure through this Roadmap may be best targeted at early stage, basic research into energy processes. This would provide a foundation for new or disruptive technologies and foster continuing basic research and innovation across the broad range of energy sources and systems. This investment would complement initiatives being undertaken through other agencies and portfolios, such as support for large scale, demonstration facilities.

In addition, consideration could be given to continued support for research infrastructure related to fusion power to facilitate linkages with international activities such as the International Thermonuclear Experimental Reactor (ITER)[57] project.

54 www.csiro.au/org/EnergyTransformedFlagship.html
55 www.ret.gov.au/energy/clean/cei/ccsfp/Pages/default.aspx
56 www.ret.gov.au/energy/energy_programs/smartgrid/Pages/default.aspx
57 www.iter.org

EXAMPLE

COASTAL SYSTEMS – NEED FOR AN INTEGRATED APPROACH

Australia's vast and diverse coastal systems are vital to our population, economy and national wellbeing. Already 85 per cent of Australians live in our major state capital cities and regional centres along the coastal fringe and, as our population grows over the next few decades, the demand for urban space, industrial development sites and services in these regions will grow significantly. Much of Australia's industrial, commercial and tourism infrastructure is located along the coast, as are our vital transport hubs.

The pressures imposed by our increasing footprint on coastal systems, combined with the impacts of climate change, present huge challenges for local, state and federal governments as they seek to adapt to and plan for future growth while maintaining the health of our marine, estuarine and terrestrial ecosystems.

The complexity of governance in the coastal zone is mirrored by the complexity of the systems themselves. Their physical, geological, biological, social and economic characteristics interact as drivers of change, components of resilience and considerations for policy makers as they seek to achieve ecologically sustainable development.

There are several facilities funded under previous Roadmaps that are responding to these issues at a scope and scale not previously achievable in Australia. These investments have begun to address major inadequacies in our understanding and modelling of the marine, terrestrial and solid earth components of the coastal zone.

However, there is widespread recognition among research communities and government at all levels that additional focus on coastal systems research is urgently required. The challenge is to avoid spreading available research infrastructure investment too thinly or creating unnecessary duplication. Investments through the marine, terrestrial, solid earth, atmospheric and urban capabilities must be focussed and integrated to provide the maximum scientific impact in high priority coastal system research areas.

Analyses of coastal research needs have recently been undertaken by a number of national and international organisations and committees[58, 59, 60, 61] and these provide useful bases for identification of priorities and evaluation of specific infrastructure needs.

58 www.aph.gov.au/house/committee/ccwea/coastalzone/report.htm
59 www.environment.gov.au/coasts/iczm/index.html
60 Morton et al, Austral Ecology (2009) 34, 1–9
61 Requirements for Global Implementation of the Strategic Plan for Coastal GOOS : IOC-WMO-UNEP-ICSU: Global Ocean Observing System Draft Document

INTEGRATED BIOSECURITY

DESCRIPTION

The risk to Australia from new and emerging pests and diseases is growing with greater international mobility, more open trade and climate change. While biosecurity events have economic and market access implications for Australia, they also have major impacts on environmental, animal and human health, along with agricultural productivity and food security.

The biosecurity research domain is evolving to better manage these risks. The current model has mainly dealt separately with plant, animal and human disease and pest incursions. This is beginning to be considered more holistically as elements of an integrated approach. This evolving model is increasingly being termed *One Health*, and is expected to form the basis for Australia's biosecurity research activities in the future.

This perspective transcends traditional detection and eradication of animal, plant or human pests and diseases to consider how location, movement and interaction of populations, modified by climate change and environmental degradation, will affect potential biosecurity events. With this contemporary view of biosecurity comes a need for access to and integration of many levels of data within an integrated secure data sharing capability. This capability is required to facilitate interaction between various disciplines and research areas.

STRATEGIC IMPACT

Geographically and genetically separate from the rest of the world, with climatic variations from tropical to alpine, temperate grasslands to deserts, Australia is susceptible to emergence and incursion of biosecurity threats from both endemic and external sources. The movement of biosecurity threats from traditional geographical regions and host vectors to new and unknown locales requires a holistic and integrated biosecurity research effort.

The *One Health* model recognises the interaction of biosecurity research with other research domains. Demand for increased production of specific food groups creates new challenges in maintaining food security and in turn creates new risks for the transmission of diseases. The continued rise of new human diseases from zoonotic sources (currently 70 per cent of all new infectious diseases) requires closer integration of biosecurity and human health resources to correctly identify and treat new outbreaks. All of these factors represent a significant and increasing threat to public health, veterinary health, plant health, tourism, trade and the economy.

CHALLENGES AND ASSUMPTIONS

Developing an Integrated Biosecurity capability will require the closer alignment and integration of researchers, research infrastructure and datasets across the broad domain areas encompassed.

While the range of domains in biosecurity research is considerable, there are many similarities in their needs. Providing appropriate infrastructure and access arrangements, linked to collaboration and data sharing tools, will best ensure the development of multidisciplinary groups spanning environmental, animal, plant and human health, and food security research areas. A challenge is to ensure that any future investment builds on the current direction of more open access and the breaking down of silos between disciplines and facilities.

An effective capability in this area would link with other capabilities including Integrated Biological Discovery, Biological Collections and Biobanks, Characterisation and the environmental capabilities.

SPECIFIC REQUIREMENTS

Various national and state agencies have developed significant and specialised biosecure research laboratories that could be brought together in this capability. Analysis of gaps and duplication within the current research laboratory network is core to the next steps in investment, prior to the integration of facilities. Links to environmental, food security, and human, animal and plant health research capabilities, both within and outside biosecure facilities, will enable researchers to create and draw upon resources of all associated fields.

These specialised laboratories need specific equipment and expertise to be available within highly biosecure research environments, particularly Physical Containment 3 (PC3) and Physical Containment 4 (PC4). There needs to be enhanced ability to conduct sophisticated analysis and scanning at both the macro- and micro-biological level, including characterisation, biological platforms and flow cytometry. Support should also be considered for the ability to breed and study both common and uncommon disease vectors on large and small scales in a biosecure environment, as well as facilities to undertake research into disease management and food security requirements in aquazoology.

Key to the Integrated Biosecurity capability is the ability to draw upon data and resources from a wide variety of sources and domain areas, from biosecure and non-biosecure areas, in multiple jurisdictions and the utilisation of equipment remotely. The investments to date provide data integration, linkage and collaboration capability for the biosecurity community and should be built upon. However, there is a need to ensure that the data linkage research infrastructure meets the needs of biosecurity researchers as a research network, rather than a network with an operations focus.

An important driver is to increase the reach beyond national security focused researchers, and to integrate interaction between biosecurity and other environmental and human health datasets and collections. This includes reference datasets for rapid species identification in order to support early pest detection.

Specialised equipment in physical containment, especially PC4 facilities, will enable new research and reduce experiment time. Remote collaboration and data sharing technologies are required to enable improved collaboration between researchers in different physical locations, including biosecure and non-biosecure areas, and across disciplines.

CYBER SECURITY

DESCRIPTION

The Australian community and economy increasingly rely on electronic systems for all aspects of daily life. Improvements in the handling, retrieval and communication of information have delivered significant economic and social benefits to the nation and the impact of these trends will accelerate into the future.

However, interconnected electronic systems have opened new areas for exploitation by criminals, terrorists and other disruptive elements. Australia needs infrastructure to support research on predicting, identifying, mitigating and preventing cyber security breaches before they occur and to rapidly analyse and resolve breaches that take place.

STRATEGIC IMPACT

Advances in the technologies we use, and the reasons we use them, are accompanied by developments in the number and type of cyber threats faced. A safer and more secure internet will be achieved through focusing on the technical and procedural challenges associated with securing electronic communications infrastructure against cyber attack and resultant cyber crime.

Organisations, institutions and critical infrastructure can be made more secure by investigating information security challenges and techniques. This will assist in protecting the finance sector and critical cyber and process control systems, such as those which regulate energy and water supplies.

The detection and reporting of inappropriate and illegal use of ICT systems is essential to analyse what attackers do and why, and to develop advice for governments and organisations on policing, policy and new legislation.

Analysis of emerging and disruptive technologies and their impact on future cyber security needs is also necessary. These technologies include quantum computing and quantum encryption, cloud computing and exascale computational capabilities.

CHALLENGES AND ASSUMPTIONS

Cyber security research is confronted by major challenges in building cooperation across multiple jurisdictions involved in this area. Security research intrinsically involves agencies that normally tightly control access to their facilities, programs and researchers.

The inclusion of this capability in the Roadmap may help to improve the linkages between organisations and researchers, so that a community consensus on priorities for cyber security research infrastructure can be formed. However, due to the nature of their work, some researchers in this field will inevitably be unable to share information on the nature of their research and facilities available to them, making such prioritisation a challenge.

The underlying research and research infrastructure needs of a Cyber Security capability will need to align with existing interests and activities in the realm of cyber security, primarily from an operations and prevention point of view. Prioritisation of research infrastructure requirements will need to be informed by broader policy work, for example, the Cyber White Paper being developed under the leadership of the Department of the Prime Minister and Cabinet.

As with several other capabilities, there are also challenges in defining infrastructure that is primarily needed for research, rather than driven by operational interests.

Additionally, consideration must be given to privacy and security principles, as these can at times effect the ability of researchers to openly share their research and collaborate in the use and operation of infrastructure.

Effective cyber security systems are essential for ensuring the integrity of Australia's research efforts.

SPECIFIC REQUIREMENTS

Key research infrastructure to draw together and support the research community will be required. Ready access to a variety of national and international databases for which new security processes, storage infrastructure and stringent audit capabilities can be tested, and methodologies and interruptive systems developed is also necessary.

Advanced tools and processes must be developed to monitor, collect and visualise large volumes of digital evidence.

In addition, the following categories of infrastructure to support cyber security research could be considered, although they may fall into the Landmark category due to the size of the investment required:

- test beds and ranges, in which new devices might be tested in isolation and then within the context of networks of other devices with the aim of detecting and understanding vulnerabilities
- immersive modelling and simulation centres in which human behaviour as individuals and groups can be facilitated and studied
- advances in communications, especially access to exceptionally fast and wide bandwidths, in order to support sophisticated national and international research and experimentation.

ASTRONOMY

DESCRIPTION

Astronomy research in Australia and internationally will continue to be focussed on understanding the fundamental physics of the universe. Such knowledge will be gained by answering key questions on the origins and evolution of galaxies, stars and planets; probing the physics of extreme environments; gaining deep understanding of the fundamental forces and forms of matter and energy that make up the universe; and studying the building blocks of life.

To address these questions, fainter signals and more distant objects must be studied across increasingly large parts of the electromagnetic spectrum, at ever higher resolution. Astronomers require access to state-of-the-art observatories and technology that span the spectrum from radio waves to gamma rays, and employ high-energy particle detectors, space craft and advanced instruments that probe a wide variety of astrophysical phenomena.

STRATEGIC IMPACT

Australian astronomy has an excellent record of research performance, discovery and impact. This success results in part from previous significant investments in astronomical infrastructure and expertise.

Astronomy pushes the boundaries of technology. Investment in new enabling infrastructure for astronomy will continue to stimulate industry.

New astrophotonic devices, radio instrumentation and image processing methods developed for astronomy can be adapted to applications ranging from new medical imaging systems to laser telescopes that detect orbiting space debris which may damage valuable satellites.

Niche industry capabilities stimulated by investments in research infrastructure for the development and testing of astronomical instrumentation are expected to extend to other research sectors, ranging from telecommunications and aerospace to medical science, environmental science, defence and national security.

The Square Kilometre Array (SKA) is an astronomy project of global importance, which will have wide ranging impact across astronomy and other fields of research. The SKA precursors are important in order to prepare for Australia's participation in the SKA and will be significant national research infrastructure in their own right. The SKA has the potential to transform data usage and management; to push the boundaries of high performance computing; and to stimulate new methodologies for data reduction and mining to extract meaningful information from huge data sets. Dual use of SKA network infrastructure may support the deployment of national sensor networks for atmospheric, ionospheric, seismic, climatological, geophysical and land use research.

CHALLENGES AND ASSUMPTIONS

Progress in astronomy is now characterised by larger, more complex, more expensive and increasingly international observatories. In contrast to previous nationally owned observatories, Australia will, in future, generally become a shareholder or partner in the most advanced international facilities. Effective infrastructure investment in this global research environment requires a long-term strategic approach, ideally providing access across a wide range of capabilities, to maximise the scientific return on investment.

One potential approach, embodied by the European Southern Observatory, is to team with countries that share research needs, to plan, manage and fund facilities. The transition to such a model may require a significant one-off capital outlay, with the potential long-term dividend being a more efficient allocation of resources. Such a model is also likely to require the negotiation of new government-to-government arrangements and funding commitments.

An important direction in international astronomy is toward large optical and radio surveys of the whole sky. Australia is well positioned to conduct and contribute to these, using existing wide-field instruments such as the Anglo-Australian Telescope (AAT), the Australian National University's SkyMapper optical telescope and the new Australia Square Kilometre Array Pathfinder (ASKAP) and Murchison Widefield Array (MWA) radio telescopes.

While there have been substantial benefits from major capital investments in Australian astronomy in the last five years, a key challenge in the coming five years is to continue the operations of these facilities. The trade-off between supporting existing and new facilities will need to be considered, in order to respond to the changing needs and priorities of the astronomy community.

Australian scientists are active in international collaborations to develop technologies for gravitational wave detection, to open a new window for astronomy. However, while gravitational wave astronomy is potentially an important emerging field for the future, the establishment of a gravitational wave observatory in Australia is not a current infrastructure priority for Australia's astronomy sector. The level of investment required to establish a gravitational wave observatory in Australia puts it in the category of Landmark infrastructure, beyond the scope of this Roadmap.

Sustaining Australia's international research advantages in astronomy will require coordination of the capture, storage and analysis of astronomical data using high quality professional services and eResearch tools. This should have a particular focus on the survey science for which Australia's astronomy infrastructure is optimised, and can also inform the development of data management systems for other science disciplines facing similar data growth and diversification.

Astronomy and Space Science are complementary capabilities, with scope for synergies, mutually beneficial research infrastructure and overlapping scientific and industrial capabilities.

SPECIFIC REQUIREMENTS

Australia's astronomy community requires a coherent and complementary mix of national observatories, access to major international facilities and their scientific data, technical development facilities, advanced instrumentation, and a robust, tailored eResearch fabric to manage and analyse the large volume of scientific data that will be produced by these facilities.

The *Mid-Term Review of the Australian Astronomy Decadal Plan 2006-2015*[62] of the National Committee for Astronomy identifies several priorities and should form the starting point when considering the research infrastructure requirements for astronomy. The priorities at the national scale include:

- positioning Australia to participate in and host the international SKA radio astronomy project, through the establishment and support for SKA precursors (ASKAP and MWA), high performance computing and data networks
- continuing support and involvement in premier national and international facilities for radio and optical astronomy, including the Australia Telescope National Facility, the Australian Astronomical Observatory and the AAT, and in addition securing long-term access to 8-metre class telescopes
- continuing involvement in the Giant Magellan Telescope
- developing an astronomical fabric of hardware and software to exploit the data deluge from current and upcoming telescopes and instruments.

Australia has a strong track record of innovation and home grown expertise in the field of astronomical instrumentation that complements and supports investments in major observatories. Building on this, the astronomy and high technology research and development sectors stand to benefit from targeted investments in specialised facilities to enable the design, fabrication and testing of advanced instrumentation for telescopes.

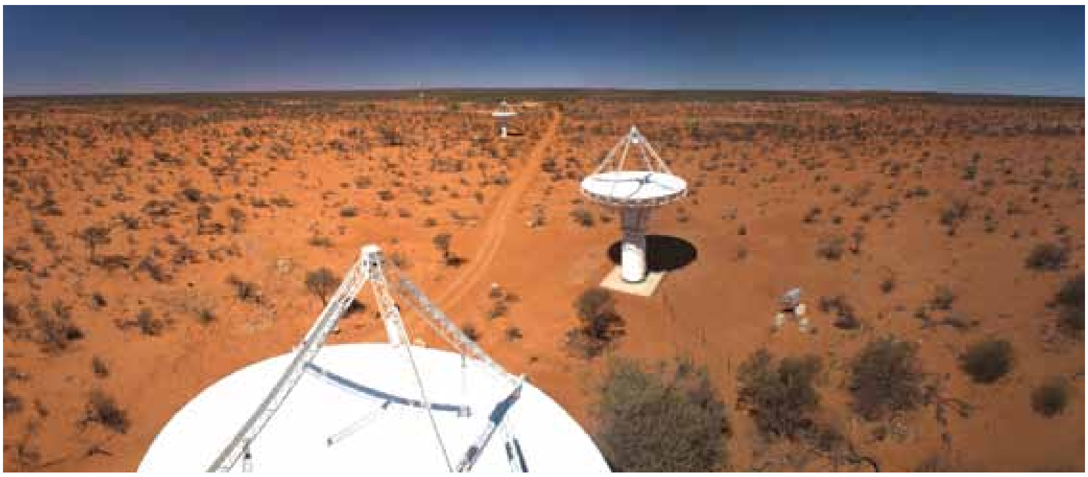


Image H

62 www.science.org.au/natcoms/nc-astronomy/documents/AstronomyDecadalPlan(2011).pdf

POPULATION HEALTH RESEARCH PLATFORMS

DESCRIPTION

Access to an integrated, national resource of population based health data will provide researchers with stronger capacity to identify the causes of disease, develop new diagnostic, preventative and therapeutic interventions and evaluate and improve clinical practice, health services and health policies. The ability to link data and develop models that cross organisations, sectors and disciplines will make a powerful contribution to identifying emerging issues, such as epidemics or adverse drug reactions, and understanding the interplay of social, environmental and biological factors in causing and controlling major common health problems.

This capability is required to link Australia's collections of population based health data and make them available to researchers through secure, privacy preserving mechanisms. The data will comprise key administrative health datasets, data from cohort studies and clinical trials, and genetic and physiological information derived from biospecimens. This capability aims to provide Australian researchers with access to linkable, de-identified data from a wide range of health datasets, across jurisdictions and sectors.

STRATEGIC IMPACT

Health services in Australia and internationally face enormous pressures relating to population growth and ageing, increasing prevalence of common chronic diseases and the costs of technological developments in health care. This creates an imperative for research to identify effective preventive interventions and to inform the allocation of health resources to achieve the best health and societal outcomes.

Australia is well placed to emerge as an international leader in research using linked administrative data. The scope and population coverage of health data infrastructure in Australia supports research that explores health differentials and inequalities, geographic and spatial aspects of health, and the effectiveness of health services. There is tremendous potential to expand existing linkages to incorporate a wider range of administrative data, such as from community-based and residential aged care services, education, child protection, crime and forensics.

Australia has a collection of high quality population based cohort studies. It is likely that these will continue to underpin a wide range of research, particularly if they are linked with administrative data and expanded to include biodata. This will enable the translation of advances in molecular biology and other fundamental sciences to solutions at the population level.

Australia also has a wide range of routine registers relating to disease, treatments and devices, which supports the clinical trials industry. Data from these sources can be linked with administrative data for long-term follow up and ongoing monitoring of adverse outcomes. This research has the potential to inform action that would reduce the use of harmful or ineffective treatments, and to redirect resources to cost-effective options.

A world-leading, comprehensive population health research platform will support a wide community of researchers from multiple disciplines, including the social sciences, environmental impact research, public health, health services research, clinical research and biomedical research.

CHALLENGES AND ASSUMPTIONS

Research that uses health data relating to individuals presents legal, ethical and privacy challenges. Conversely, technological advances are delivering new tools to protect privacy and improve data security. A mutually satisfactory balance with regard to legal, ethical and privacy challenges is likely to be achieved by a combination of policy-centric and technology-centric measures.

Existing cohort studies, registers and data from clinical trials are managed by diverse public and private sector entities using a wide variety of access models. Currently, many cohort studies and registers rely on short-term project funding to support their maintenance, follow up and tracking activities, challenging their long-term sustainability.

In order to understand and find solutions to complex health problems, researchers need access to large volumes of data from a complex variety of sources, as well as the expertise and technological capability to manipulate this data. This will enhance cross-disciplinary, cross-sectoral and cross-jurisdictional engagement and promote collaborative research.

Research using large scale population data is highly dependent upon capabilities in biostatistics and bioinformatics and this capability will therefore need to interact and link with the Integrated Biological Discovery and Biological Collections and Biobanks capabilities. In addition, there need to be linkages with the Translating Health Research capability area.

SPECIFIC REQUIREMENTS

There is a requirement to expand Australian research capabilities for health data linkage and to ensure there is new or upgraded infrastructure, allowing for coordinated and efficient acquisition, management, analysis and governance of health data.

This capability will build on existing infrastructure. Incorporation of a wider range of data will involve extensive stakeholder liaison and policy development, as well as investment in further development of systems for the secure storage, management, transfer and archiving of data, and for performing data linkage.

The Australian Government has signalled that its linked data (including key Medicare Benefits Schedule, Pharmaceutical Benefits Scheme and aged care data) will generally only be available to researchers through on-site data laboratories or secure remote access facilities. A Cross-Portfolio Data Integration Committee has been established to provide strategic and collaborative leadership regarding the use of Commonwealth data assets in data integration projects for statistical and research purposes. This Committee will support the development of effective governance and risk management practices for projects involving Commonwealth data. The Committee aims to create a consistent and unified approach to facilitate linkage of social, economic and environmental data for statistical and research purposes.

Partitioned workspaces or enclaves for hosted research studies can meet the need for secure access but significant additional investment will be required to meet growing demands from a broader group of researchers.

Incorporation of data from cohort studies, registers and clinical trials into the platform will require the development of new mechanisms to govern and manage these datasets as an open access resource while still maintaining appropriate arrangements with regard to intellectual property.

Infrastructure to support the efficient ongoing operation of cohort studies and registers will be required if they are to form a key part of this platform. This could include shared infrastructure for cohort recruitment, maintenance and tracking as well as for the storage, management and linkage of data.

In addition, expanded eResearch infrastructure and expanded metadata capabilities will be integral to maximising access to and benefit from information made available by the Population Health Research Platforms, Biological Collections and Biobanks and Integrated Biological Discovery capabilities. Specific eResearch infrastructure includes a range of capability specific access tools and resources for data management, manipulation and analysis.

TRANSLATING HEALTH RESEARCH

DESCRIPTION

Bridging the gap between the discoveries made by researchers and treatment received by patients not only improves the quality of patient care and health outcomes but also benefits the nation's economy. To capture the full value of Australia's public and private investment in health research, preclinical capabilities are required.

Translating health discovery into improved health outcomes requires an underpinning set of research infrastructure that allows individual discoveries to be progressed.

Translating health research is the process that leads from basic medical research to sustainable solutions for public health problems. It aims to improve the health and longevity of the public and depends on developing links between basic scientific discoveries and clinical investigation, informed by evidence from the social sciences.

This capability will provide effective and efficient pathways for potential therapeutics and medical devices to move from the discovery stage into, and through, preclinical testing, clinical trial design and clinical trials, in order to meet the various requirements of regulators for release. Supporting the translation of research findings into sustainable improvements in clinical and health outcomes is required to maximise research outcomes.

STRATEGIC IMPACT

Breakthroughs in therapeutic and other medical treatments have the potential to improve Australians' quality of life. Australia has significant strengths in health and medical research but requires additional capacity to support the effective and efficient transition of research from the laboratory. Platforms for translating health research will facilitate this, ultimately leading to faster, more cost-effective drug therapy development and implementation.

Increasing the rate of development and implementation of effective new diagnostic tests, devices, treatments and preventive interventions through more efficient translational pathways and services will produce results at multiple levels. This will improve population health in general; generate economic savings through more efficient processes; decrease the cost of drugs; raise the quality and efficiency of clinical trials; improve translational medicinal chemistry; reduce the health care burden at the national level as well as on individual institutions; provide flow on benefits to Australian industry; and strengthen international engagement and collaboration.

Major patient cohorts and clinical collections will be able to be analysed nationally in a discovery phase utilising genomics to uncover new biological pathways that can better inform drug development and pharmaceutical use. Individualised treatments will be the next goal with the identification of specific biomarkers that can be developed into diagnostic assays.

The development of new medical and preventative treatments offers potential for exports and job creation in local manufacturing industries. Investment in this capability will allow Australia's health system to remain internationally competitive and ensure Australians have access to health outcomes commensurate with other developed countries.

CHALLENGES AND ASSUMPTIONS

This capability area intersects with most areas of the health sector. The wide scope of this sector, the number of change initiatives underway and the breadth of research infrastructure requirements present challenges in the process of identifying and prioritising research infrastructure gaps.

In addition to infrastructure requirements, this capability faces specific challenges in sourcing funding for pilot studies, meeting ethics approval requirements, recruiting clinical trial participants, and managing interactions between clinical researchers and industry.

There are substantial overheads involved in all translational activities, but this is a particular issue for research aimed at public good outcomes rather than commercial opportunities.

The success of this capability depends upon interaction with the Integrated Biological Discovery, Characterisation, Population Health Research Platforms and Biological Collections and Biobanks capability areas. It will also be important to consider other policy work in this area, such as the report developed by the Clinical Trials Action Group[63], in order to align any future initiatives.

SPECIFIC REQUIREMENTS

Image I

Current investments represent the first steps in helping researchers to bridge the translational gap from basic to potential therapeutic application.

Infrastructure is now required to support research into medical devices, drug delivery systems, diagnostics or surgical devices.

A national, integrated, systemic approach to meet the needs of therapeutics researchers will depend on an enhanced infrastructure capacity for clinical trials, as well as associated collaborative activities and information sharing tools.

Ongoing support for the manufacturing of pre-commercial amounts of new therapeutic biological products with the appropriate support structures to foster Phase I and Phase II clinical trial activity is essential. An integrated network of preclinical testing facilities is needed, including absorption, distribution, metabolism, excretion and toxicology, animal disease models and biomarkers testing.

Additionally, a national small molecule repository and a national screening network to identify small molecule drug candidates are necessary. Enhanced and more integrated primary and secondary drug screening capability is also required to enable deeper and more insightful analysis of drug action.

63 www.innovation.gov.au/INDUSTRY/PHARMACEUTICALSANDHEALTHTECHNOLOGIES/CLINICALTRIALSACTIONGROUP/Pages/default.aspx

Continued support is needed for existing infrastructure for mammalian and non-mammalian cell-based production of recombinant proteins as potential therapeutics. This includes the supply of therapeutic monoclonal antibodies in adequate quantities for evaluation, and of human cells or cellular based products for transplant. Possible enhancements relating to emerging cell therapies may include support for the growth of stem cells, mature cells, cell lines and animal cells with links to bone marrow and cord blood facilities.

Support for a national small and large animal preclinical trials and testing facility with an increased capacity in high quality animal pathology and phenotyping should be considered.

Cross-disciplinary bioinformatics is required to address the convergence of high end computing, computational biology and molecular sciences, which has implications for translational research.

CULTURES AND COMMUNITIES

DESCRIPTION

Australia's humanities, arts and social science researchers are recognised internationally for delivering solutions to challenging questions facing society and for bringing their expertise to bear on complex issues, such as in health, the environment, social cohesion and security. Their work encompasses law, society, education, identity, economics, business, governance, history, culture, language and creativity. Their fields link universities, government agencies, collecting institutions and the creative industries.

The Cultures and Communities capability is required to make both old and new data discoverable and reusable and to extract greater value from existing collections that are as varied as statistical data, manuscripts, documents, artefacts and audio-visual recordings. These materials reside in a diverse array of private and public repositories, many of which are unconnected. This national, collaborative research infrastructure will provide researchers with the resources and access to large data sets that a single institution would be unable to establish and maintain.

Interoperable, standardised databases and networks will enable manipulation and comparison of these variable research materials. Dedicated tools will enable researchers to assemble, combine and analyse data sets at a scale not previously possible, to produce holistic answers to complex questions and link researchers across virtual communities nationally and internationally.

STRATEGIC IMPACT

The implementation of this capability will have major, long-term ramifications. The results of humanities, arts and social science research are of immediate interest to the general population, policy makers and the wider research community.

The objectives and impact of this research will be accelerated and more widely distributed through streamlining access to Australia's data holdings, enabling discovery of previously hidden data, stimulating connections and synergies, and catalysing innovative research. Providing easy access to data and powerful analysis methods will enable effective data mining and re-use, maximising the return on previous research investment.

Social science studies, including Indigenous studies, contribute significantly to our understanding of identity and change. Retrospective studies in conjunction with current cultural studies can enhance the development of solutions for contemporary challenges across a spectrum of fields.

Analysis of immense, complex and diverse data sets through new tools will reveal implications and insights not possible in the past. Tools that permit efficient collation, manipulation and recombination of diverse data sources will enable new research fields to be pioneered.

Policy makers and the broader community will benefit greatly from the results of research enabled by this capability. When combined with the accessibility afforded by modern digital infrastructure, geographically dispersed Australians will be able to access information relevant to their cultures and histories. The interactive nature of the capability will allow individuals and groups to contribute to the data as well as to use it.

CHALLENGES AND ASSUMPTIONS

This capability area will provide fundamental and pervasive support for the majority of the capability areas articulated in the Roadmap. For instance, the integration of data from this capability with environmental data will increase understanding of human impacts on our environment; and enhanced outcomes are achievable through the combination of lifestyle information with research on specific health challenges such as diabetes.

As well as contributing to research undertaken in other capability areas, this capability depends significantly on the eResearch and Digitisation Infrastructure capabilities. The implementation of the Digitisation Infrastructure capability will unlock research data held across Australia, the legacy of massive research investment in the past. Once digitised, the uses for data will be almost limitless when made available through the research infrastructure of the Cultures and Communities capability.

Much of the Cultures and Communities capability will be based on eResearch tools and techniques. However, while the cultures and communities research sector has embraced eResearch knowledge, skill levels vary widely across the sector, and skills and training need to be addressed by researchers and research organisations.

The diversity of the sector and the disparity of data formats in existing collections, as well as inconsistent metadata, are challenges for this capability and one of the key rationales for its development.

Research data in the domain of cultures and communities may be sensitive from cultural, individual or other perspectives, and solutions to this challenge need to be integrated at a systems level. Access to the large amounts of data owned by individual institutions will require commitment by those institutions and the wider research community.

At a broader level, there is a challenge in ensuring researchers have access to resources to guide them in the best methods related to their fields. This includes how to best capture and store the type of data used in their research area, the most appropriate repositories for their type of data and the techniques most appropriate for dealing with non-digital data.

The breadth of this capability and the diversity of its disciplines will make implementation a challenge. Rational and effective investment will demand a high level of consultation across the nation and among diverse institutions. The establishment of a body to oversee and guide the implementation and ongoing development of the capability may need to be considered to ensure the greatest benefit for the sector.

SPECIFIC REQUIREMENTS

Purpose-built, easily accessible, interoperable and dedicated eResearch platforms will comprise networks of databases, spaces for collaboration, resources and tools, enabling access to and analysis of diverse datasets. Accessible from researchers' desktops, these platforms will link individuals and groups of researchers with virtual research communities nationally and internationally. Platforms may be formed around research themes which bring together tools and datasets which will bring the most benefit to the research community.

A variety of networking and access tools are required to facilitate use of the diverse data currently stored in repositories. Not only must current repositories be made accessible to researchers, services are required which enable the conversion of data, currently in a variety of formats, into forms which are useable by a variety of researchers. These access and format conversion tools will be at the heart of unlocking our current repositories of data.

Protocols must be established for future data sets which are Open Archival Information System[64] compliant. This will ensure that data is generated and made available in appropriate formats with proper metadata descriptions, is captured and managed to international standards, is curated efficiently and is discoverable and accessible.

The power of the capability can only be realised if disparate data sets can be connected, combined and analysed. To do this, tools are required which specifically address the needs of the sector to capture, analyse, visualise and interrogate the types of data of relevance to the sector including documents, audio-visual files, images and statistics.

The provision of virtual spaces for collaboration will be of particular importance in fostering effective use of these data resources and promoting interdisciplinary work.

Illustrative example: A potential digital atlas of Australian people

A digital atlas of Australian people would unite disparate social and cultural research data with collection information, within a broad geographic framework, and could be a powerful tool for researchers responding to questions of national urgency. It would provide a platform for collaboration and enhanced access to a range of source material (collections) across a wide sweep of disciplines within the humanities and social sciences, while facilitating links to relevant research on the environment, population or health. As an example, researchers investigating water flows and usage along the Murray Darling river system might enrich environmental studies with research on the varied histories, economies or sociology of different areas, while accessing original source material from libraries, museums and archives. Communities could be directly involved in research projects and policy debate through interactive tools.

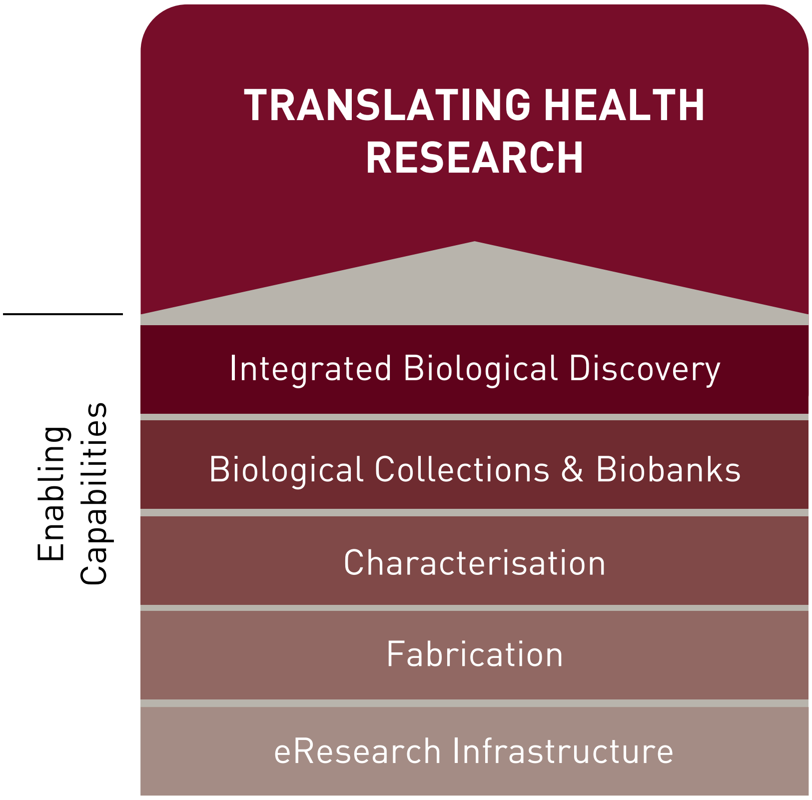
64 www.nla.gov.au

ENABLING CAPABILITY AREAS

The enabling capability areas support both research outcome targeted capabilities and each other. They form an integral part of the research infrastructure landscape and underpin multiple fields of research endeavour.

As an example, the Translating Health Research capability area relies on the research infrastructure, services and outcomes from a selection of the enabling capability areas, as depicted in Figure 4.

Figure 4 – Example of enabling capabilities supporting a research outcome targeted capability



An important characteristic of enabling capability areas is that they support common use of research infrastructure and encourage cross-disciplinary interactions.

INTEGRATED BIOLOGICAL DISCOVERY

DESCRIPTION

The Integrated Biological Discovery capability is a set of critical underpinning platforms comprising infrastructure for genomics, proteomics, metabolomics and phenomics (mouse and plant) research, as well as fostering the pervasive and integral fields of bioinformatics and biostatistics. A sophisticated and cohesive national biomolecular capability network is required to ensure that strategically important research is facilitated while promoting the parallel goals of knowledge diffusion and collaboration.

These platforms will provide a sophisticated and cohesive national biomolecular capability network that will integrate information on genes, proteins, interactions and metabolomics pathways. This network will build understanding of the function of complex biological systems and how they may be optimised for biomedical, industrial, agricultural, food science and environmental applications.

This capability will mark a significant advance for systems biology in Australia, which is a highly interdisciplinary field that brings together biologists, engineers, chemists, physicists, mathematicians and computer scientists.

As we move towards understanding biology at the systems level, access to large data sets holding many different types of biological information has become crucial. However, the extensive use of next generation sequencing and other high-throughput technologies also poses new challenges in coping with and interpreting the vast volumes of data being generated. Bioinformatics and biostatistics capabilities are needed to harness the full potential of this data and allow for integration across platforms.

STRATEGIC IMPACT

The completion of numerous global genome projects and the advent of next generation sequencing capability will enable the sequencing of all organisms, tissues and cells of interest to researchers. Single gene sequencing is no longer the common practice; rather the sequencing of families of genomes and their epi-genomes is the reality. The rapid development of a wide range of 'omics (for example, transcriptomics and metabolomics) is transforming biological research, and the need to link the genotype to the phenotype is driving the development of new research approaches. The scale of data and information being collected is unparalleled in the history of biological research and those nations that can generate, and more importantly, mine this resource will be well placed to reap the rewards that will flow to the health, industrial, agricultural and environmental sectors.

The current revolution of biological science and techniques is inherently coupled to the information technology revolution that began in the late 20th century. The availability of the required resources to harness the outputs of the technical advances provided by new technologies is the key to maximising results from our investments in this area.

Bioinformatics and biostatistics provide the basis to achieve this goal. These capabilities provide the necessary context to data and enable the scientific community to best utilise the outputs of advancing technology, within and across formerly disparate domains.

Discovery phase research utilising genomics, metabolomics and proteomics can uncover new biological pathways to better inform drug development and pharmaceutical use. Individualised treatments will be the next goal with the identification of specific biomarkers that can be developed into diagnostic assays. This will improve both health outcomes and the economics of health care. Already biotechnology is reaching into this realm with new personalised biological treatments such as for breast cancer and rheumatoid arthritis.

Mouse models of human disease play a key role in the interpretation of the human variability that currently limits translational medicine. Australia's unique suite of mouse phenomics infrastructure and excellence in both translational medicine and mouse phenomics position this nation's researchers to play an important role in the next phase of unlocking the human genome and producing new health treatments.

Large scale studies of agricultural populations would strengthen Australian agri-food and other industries' international competitiveness and environmental sustainability. Additionally, genomic data will improve the understanding of Australia's unique flora and fauna and the sustainable management of Australia's biological heritage. In particular, environmental metagenomics is an emerging technology that is likely to play an important role in this area.

CHALLENGES AND ASSUMPTIONS

The existing biological capabilities provide a launching pad from which to build a fully integrated biosystems research infrastructure capability supporting environmental, agricultural, medical and biosecurity bioscience areas.

While coordination between component facilities provides centralisation and avoids duplication and fragmentation, Australia must expand capability into new and complementary areas of research infrastructure if it is to provide essential support for the biosciences.

Greater integration between disciplines is required to deal with emerging and complex issues that are being examined by researchers. An expanded and enhanced Integrated Biological Discovery capability area will facilitate coordination between the 'omics, bioinformatics and relevant aspects of other capabilities.

Moreover, the platforms must be nimble and open to new technological breakthroughs, as well as to supporting other 'omics technologies, such as transcriptomics and glycomics. They should encourage multidisciplinary collaborations and links with international repositories, networks and peers. Existing infrastructure provides a platform for international collaboration in biomedical research and this should be further built upon.

A continuing challenge in this area will be the lack of bioinformaticians and biostatisticians and the need to embed these skills within biological research groups. Computational analysis has now become a bottleneck for research progress, both in Australia and globally.

The Integrated Biological Discovery capability will be most effective if it has strong linkages with the Characterisation, Biological Collections and Biobanks, Population Health Research Platforms and Translating Health Research capabilities. It is also an underpinning requirement for a number of other capability areas, in particular, Integrated Biosecurity, Terrestrial Systems and Marine Environment.

SPECIFIC REQUIREMENTS

Ongoing funding for the existing capabilities that support this broad platform is essential to ensure Australia maintains its position as a leader in the integration of biological platforms globally.

Bioinformatics and biostatistics

Bioinformatics is the creation and advancement of databases, algorithms, computational and statistical techniques and theory to solve formal and practical problems arising from the management and analysis of biological data. Biostatistics is the manipulation of the information derived from these processes.

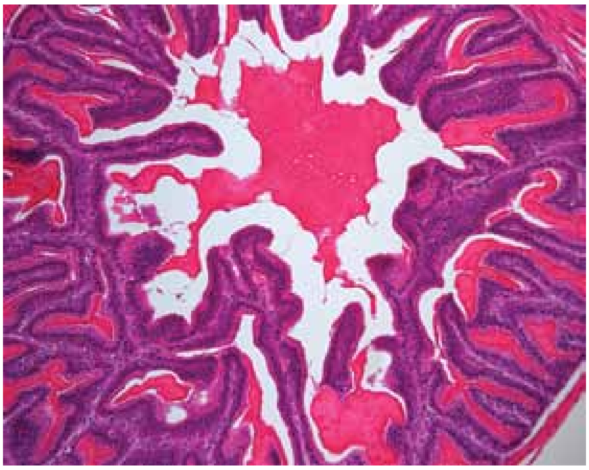


Image J

Biomolecular science has become inextricably linked to informatics and eResearch infrastructure. Sophisticated bioinformatics and biostatistics tools and expertise are required to support experimental planning and quality control, storage, data curation, integration, visualisation and ultimately mapping to a biological context. In the next decade it will be crucial to ensure bioinformaticians, biostatisticians and computational scientists are increasingly embedded within biological laboratories augmenting the critical mass available through separate facilities.

There is an underpinning bioinformatics and biostatistics requirement to support the full 'omics suite of research.

Framework data

The limited availability and high cost of generating, storing and making accessible high quality quantitative framework data constitutes a major bottleneck in the application of mathematical modelling in biology and medicine. The generation of such data is generally not feasible for small research groups. Developing priority datasets should therefore be considered, as it would make information available for application to research questions across the breadth of scientific disciplines.

Genomics

Genomic science has been transformed in the last five years. To keep pace, Australian researchers require additional instrumentation and infrastructure, including associated robotics, to handle large scale sequencing that is now fundamental to many capabilities. With the rate of technological innovation accelerating and many emerging technologies, such as single molecule sequencing, the flexibility to adopt and develop new technologies will be crucial. For example, RNA and epigenomic analyses using both sequencing and microarrays remain essential tools for biological analyses. The cataloguing of the vast array of RNA transcription factors is also an emerging area important to understanding gene regulation, gene expression and disease.

Proteomics

Protein science requires additional capacity and capability in mass spectrometry, particularly leading edge instrumentation with high duty cycles, higher sensitivity and resolution. In addition, there is also a requirement for greater capacity for amino acid analysis and N-terminal protein sequencing. Monoclonal antibody development and production is a growth area and requires increased capacity, principally through automation.

Metabolomics

Mass spectrometry along with gas and liquid chromatography are essential requirements for metabolomics research. Nuclear magnetic resonance (NMR) spectroscopy has growing value in molecular identification and structural elucidation. The development of molecular libraries is also necessary and will allow for the continued standardisation of metabolomics research.

Image K

Plant phenomics

Continued investment is required to develop novel imaging technologies to complement existing tools, particularly image analysis software, 3D modelling capacity and database management. In addition, improved ICT infrastructure is needed for accessing, interrogating and sharing large phenomics datasets and to integrate plant phenomics data with high-throughput gene sequencing.

Mouse phenomics

It is desirable to integrate the current mouse exome analysis capability with other phenomics capabilities and with translational medicine. Parallel efforts in mouse and human exome sequencing and phenomics capabilities should be initiated and support is required to establish framework collections and mouse model capabilities including repositories.

Additional investment is required for exome sequencing programs in mouse models and alignment of these efforts around key research strengths in Australia (such as cancer, malaria and immunological research). Further investment in large scale phenotyping as well as integrated phenomics specific data capture, storage and access to DNA and phenotyping data sets is necessary. This should be undertaken in conjunction with major overseas consortia to ensure open access to important international collections.

Other requirements

Australia's ability to participate in the international arena and collaborate with the world's leading scientists is enhanced by ongoing membership of large international consortia as well as the development of partner laboratories or mirror facilities. Continuing investment in such initiatives is a priority.

The data generated across the 'omics suite requires significant database development and analytical software for interpretation, management, storage and processing.

Access to multi-modal imaging technologies, such as molecular, cellular and whole animal imaging (including NMR spectroscopy, synchrotron science and microscopy) is an underpinning requirement. Additional requirements include high-throughput chemical screening and protein production, as well as facilities to hold small and large experimental animals.

It will be important to support the integration of emerging technologies and diagnostics with commercially available tools, in particular new measurement paradigms developed outside the biological sciences community.

The development of integrated research facilities that can simulate the clinical setting would support Australia's position internationally. Such a facility would require infrastructure to support small and large animal and human research with ready access to imaging technology, 'omics suite sequencing and bioinformatics platforms[65]. However, this is likely to be Landmark infrastructure and as such would fall outside the scope of this Roadmap.

A final requirement is ongoing access to information networks and repositories both nationally and internationally, as scientific discovery is increasingly a global commodity.

65 An example is outlined by the Division for Clinical Research Resources: Guidelines for General Clinical Research Centers Program (M01) National Center for Research Resources, National Institutes of Health, Department of Health and Human Services, October 2005

BIOLOGICAL COLLECTIONS AND BIOBANKS

DESCRIPTION

Biological collection and biobanks are systems for the management of tailored facilities that collect, store and distribute biological resources regardless of origin in a secure and accessible form. They are an innovative approach to the conservation and sustainable utilisation of diverse genetic resources, including samples of species of flora and fauna and human tissue.

Biological collections support the understanding of the variability of biodiversity and also include the storage and characterisation of germplasm, which will support the preservation of natural and crop biodiversity. They provide links to the resistance to or weakness from introduced flora and fauna, and provide a platform for the preservation of native species.

Biobanks offer unique opportunities to research, assess and document genetic diversity and define new health research directions. The specimens kept in biobanks are linked to measures of clinical outcomes such as survival time, response to therapy or time for disease recurrence, which can contribute to more robust conclusions for research in the health field.

STRATEGIC IMPACT

The information derived from biological collections and biobanks has important applications in preventative medicine, plant phenomics, animal models and sequencing and conservation of unique biodiversity. This capability area will contribute to the international competitiveness of Australian researchers and will promote collaboration with international research organisations.

Australia's sizable cohorts of clinical patients, collections of agriculturally and environmentally significant plants, insects and microorganisms, and unique flora and fauna represent tremendous opportunities for discovery and provide underpinning information for a myriad of research challenges. Such collections will provide Australian researchers with infrastructure essential to advances in biomedical and environmental research.

Biological collections and biobanks offer toolsets for accelerated knowledge and scientific discovery. They provide information on Australia's terrestrial and marine biodiversity that is essential for natural resources management, understanding impacts on Australia's biodiversity and mapping threats from invasive species, for example.

Nationally coordinated biobanking infrastructure to facilitate access to biospecimens (and associated data, such as clinical data for health biobanking) will result in improved outcomes for patients and the production of high quality, credible research. Such research has a clear link to the development of improved diagnostic pathways and more targeted and effective therapies for patients. This in turn produces economic efficiencies through the development of cost-effective allocation of health funding to the most appropriate therapy for each patient.

Access to health biobanks and associated bioanalysis has the potential to improve research outcomes relating to the prevention, diagnosis and treatment of a wide range of serious and life-threatening illnesses including cancer, heart diseases, diabetes, inflammatory bowel disease, arthritis and dementias.

The benefits of a nationally coordinated approach to biospecimen collection and storage include access to larger sample sizes for research, increased awareness of specimen availability and standardised quality and consistency of sample collection and preservation. Increasing economies of scale will facilitate the critical long-term follow up of samples. Any such capability would need to coordinate the disparate yet valuable array of collections that already exists across Australia.

CHALLENGES AND ASSUMPTIONS

Image L

Biological studies require appropriate collection and storage of fixed or frozen tissue samples as well as the mechanisms to facilitate timely access to these biospecimens for analysis. This relies on networked, easily accessible biological collections and biobanks, which will provide repositories for a diverse range of biological samples.

Currently there are many small collections housed in individual research laboratories or museums. The bulk of these collections comprise research specific samples. Australia currently lacks national coordination of malignant and benign tissue, blood or other bodily fluid samples and plant, animal, soil, water and atmospheric samples. This capability will be an important part of reducing this fragmentation of collections in Australia.

One challenge will be to link the data from biological collections with broader environmental observation datasets. Integration of these datasets is fundamental to Australia's capacity to manage its biodiversity in an intelligent and sustainable way.

More significantly, Australia will need to establish secure storage and ethical researcher access to individual health records and biological tissue samples[66]. Government agencies are working to address these issues, as discussed further in the Population Health Research Platforms capability. Strong integrated management systems for archived collections are an underlying requirement across the research sector, incorporating adaptive data models and processes for the management of intellectual property, policy issues, services and maintenance.

It will be important to ensure that this capability takes into account policy work and initiatives being undertaken by other agencies and organisations, such as the National Health and Medical Research Council's *National Health Research Enabling Capabilities*[67] scheme.

66 This work will need to occur within the broader policy context, including the government's Personally Controlled Electronic Health Record initiative http://www.nehta.gov.au/
67 www.nhmrc.gov.au/grants/apply-funding/infrastructure-support

This capability is inextricably linked with the functions of the Integrated Biological Discovery capability because of the requirement for genotype and phenotype analysis of the samples, and the use of bioinformatics and biostatistics to support understanding at a systems level. Close links to the Marine Environment and Terrestrial Systems capability areas will assist in providing a systems approach to ecological research and links to Integrated Biosecurity will assist with identification of pest species. In addition, the imaging processes provided through the Characterisation capability and the resources of the Digitisation Infrastructure capability will be essential.

SPECIFIC REQUIREMENTS

Nationally coordinated and networked Biological Collections and Biobanks are required. The complex nature of developing such facilities will require nationally agreed protocols and standards for the collection, storage, curation and access to the samples. This should take into account international best practice.

Secure storage under controlled temperatures and humidity, with backup systems, are necessary. Barcoded archiving of samples accessible via robotic retrieval systems is also desirable.

Laboratory information management systems including data dictionaries, data integration and linkage are also essential to maximising the benefits of these collections.

CHARACTERISATION

DESCRIPTION

Characterisation is the direct analysis of the structure, chemistry and physical properties of materials. Materials may be soft (tissue, cellular, polymeric) or hard (metals, ceramics, semiconductors). Analysis incorporates imaging, spectroscopy and scattering processes, and includes studies of morphology, dispersion, structure, composition and bonding. Characterisation is recognised as a platform technology that is essential for many research disciplines.

There is a continuing need to enhance infrastructure in this capability to ensure Australian researchers can continue to work with state-of-the-art technology. These enhancements are likely to include adding a temporal dimension to allow dynamic processes to be probed in real time *in situ*, and the combination of measurement modalities so that varied materials' properties can be simultaneously measured at high-resolution.

STRATEGIC IMPACT

The Characterisation capability plays a key role in research across the physical, engineering, life and environmental sciences. It underpins many fundamental research efforts and the development of new and emerging technologies. From atoms to molecules and crystals, from cells to tissue, through to entire organisms, characterisation enables research within and between many disciplines, from archaeology to zoology, from materials science to medicine, and from life sciences to Earth sciences.

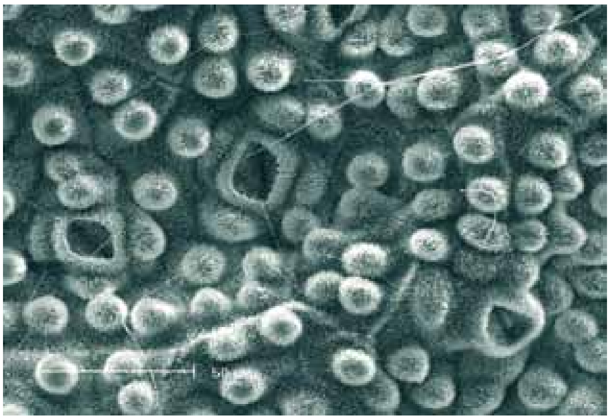


Image M

The pervasive nature of this capability area is exemplified by its application in the resolution of important and diverse research questions. This is evident through examples such as the use of electron microscopy to determine the 3D structure of human islet/beta cells to provide insight into diabetes; the use of focused ion beams to obtain the structural morphology and elemental composition of particles recovered from crime scenes, to assign a possible source for this evidence; and the use of magnetic resonance imaging (MRI) to examine micro-distribution of nutrients in cereal crops.

Characterisation infrastructure allows scientists, engineers and industrial researchers to understand and quantify diverse materials, both manmade and biological. As well as having the ability to design and develop advanced materials, Australia needs to be able to develop high performance processing routes with low environmental impact for existing materials.

CHALLENGES AND ASSUMPTIONS

Previously funded facilities have a strong history of collaborative and integrative provision of infrastructure; this should be encouraged across the entire Characterisation capability. Opportunities for enhanced collaboration and interaction between capabilities, including fabrication, should be actively sought. Mechanisms for collaboration could include networks of people, ICT and cross-research infrastructure engagement.

To ensure the full scope of this capability area is covered, facilities should be widely accessible. Future funding should serve the research and innovation system broadly, encouraging collaboration between universities, government, independent and private sector organisations. Moving into the future, there should be a balance of centralised and distributed facilities to support accessibility and collaboration.

Modern characterisation instrumentation requires a high level of specialist expertise to select the appropriate techniques and to obtain excellent data. As characterisation grows in complexity in order to address more challenging research questions, the gateway to discovery will shift from the instruments themselves to the subsequent offline visualisation, analysis and simulations required to deal with increasingly large and multidimensional datasets.

In order to manipulate the complex large scale datasets produced by this capability, it will become increasingly important to have specialised computational modellers, expert data analysts and biostatisticians, in addition to expert technical staff to support the instruments.

In Australia, the uptake of combinatorial and high-throughput experimental methodologies has been slow outside of the life sciences and addressing this will be a future focus.

A challenge exists to build on the world-class platforms established to date, such that they are transformed to operate at higher spatial and chemical resolutions, in all spatial dimensions and real time *in situ*. Further challenges lie in providing integrated expertise and instrumentation, genomic characterisation and high-throughput screening.

Characterisation is a pervasive form of research infrastructure which serves a broad range of disciplines. This capability will benefit from strong linkages and interaction with the Fabrication capability, along with the Integrated Biological Discovery capability. Due to its underpinning nature, it supports many other capability areas, such as Sustainable Energy, Translating Health Research, Solid Earth, Integrated Biosecurity and Biological Collections and Biobanks.

SPECIFIC REQUIREMENTS

The highest priority is continued support for current facilities and expanding them to realise the benefits from recent advances in certain characterisation technologies.

High level microscopy and microanalysis

Advanced microscopy and microanalysis is a key enabler for world-class research outcomes across numerous disciplines. Future investment should be guided by user demand and usage, by developments in next generation equipment and by ensuring broad based access.

Further investment in technologies such as high-resolution electron microscopy (including cryo technologies), advanced ion mass spectroscopy and ion beam techniques, and super resolution laser microscopy are several of the advanced platform technologies that should be considered.

Image N

Enhancement of the Australian Synchrotron

As an enabling facility, the Australian Synchrotron provides essential infrastructure that supports research across most of the sector.

The Australian Synchrotron currently has eight world-class beamlines. A ninth beamline, which is under construction, will be a world-leading facility for health and imaging sciences and will support a clinical research program.

Further investment should include ongoing support to enhance the facility's capacity to service the needs of the research sector. Any further funding could support additional beamlines, such as one suitable for Earth science research, upgrades to the current accelerator or major upgrades to the existing facilities. In addition, further support for Australian researchers to access international synchrotrons should be considered.

Investment planning should take account of the *2010 Science Case for the Development of the Australia Synchrotron*[68], as well as international trends in synchrotron science, existing strengths and demand for synchrotron science in the Australia.

Imaging

Imaging is a rapidly evolving field and while hardware can be upgraded, it is often more effective to purchase new systems as they become available. Increased capacity and ongoing support is required for existing facilities at a level that enables them to continue as world-class.

A range of imaging technologies will allow the strengths of different modalities to be exploited, for example to give more accurate diagnosis and monitoring of disease, or for plant science research to support a sustainable agriculture industry. Support for magnetic resonance imaging (MRI), positron emission tomography (PET) and other molecular imaging modalities such as single photon emission computed tomography (SPECT), optical (luminescence and fluorescence), ultra-sound and THz imaging should be considered (noting that THz imaging has other applications, including microscopy and synchrotron science).

Investment in extreme field magnetic resonance imaging will support biomedical research and position Australia to lead developments in cutting-edge physics, engineering and imaging applications.

Establishment of a multi-modality human imaging and therapy research facility could also be considered. The facility would enable biomedical and clinical scientists to implement new therapies and assess their efficacy and side effects using the most advanced imaging technology available. This facility would build on the complementary and simultaneous use of different imaging techniques.

Advanced spectroscopy

Nuclear magnetic resonance (NMR) spectroscopy is an essential platform for research in the molecular and material sciences, including chemistry, structural biology, biomedical sciences and metabolomics. It allows the study of structure, function, dynamics and interaction at the molecular level. The provision of high end NMR instrumentation as part of national collaborative research infrastructure should be considered.

68 www.synchrotron.org.au/index.php/about-us/australian-synchrotron-development-plan

There are also other spectroscopic probes used for molecular characterisation, employing high-energy to low-energy photons, positrons, electrons and other subatomic particles. These would include, for example, mass spectroscopy, electron paramagnetic resonance (EPR) spectroscopy, Raman and infrared spectroscopy, Auger and Doppler broadening energy spectroscopy (DBES). Australia has strong expertise in many of these common characterisation methods, however, it will be important to ensure that the level of demand and user base are of a scale requiring national, collaborative research infrastructure. In addition, emerging areas of characterisation such as ultrafast and highly spatially resolved spectroscopy could be considered in the future.

Enhancement of the Open Pool Australian Lightwater (OPAL) reactor

As another enabling facility, the OPAL reactor provides vital infrastructure supporting a wide range of disciplines. In addition to the deuteration facility, it incorporates a suite of seven neutron beam instruments with a further six at the construction or design phase.

Additional beamline techniques should be considered in the context of the Australian Nuclear Science and Technology Organisation's *Corporate Plan 2010-2015*[69] and looking at scientific needs in the context of instrument usage, user demand, available instrumentation options, upgrades and long-term operating requirements.

One possibility for expansion would be the addition of a positron beamline. This would enable fundamental studies in PET mechanisms and material characterisation; contributing to medical diagnostics and therapy, along with other biological and commercial applications.

High-throughput and combinatorial materials science

High-throughput methods in research involve integrated, often highly automated, facilities for synthesising libraries of new materials and testing a range of characteristics in parallel, rather than in series as is traditional. In general, the equipment required for high-throughput and combinatorial approaches to materials discovery differs from the equipment available in current characterisation facilities.

High-throughput and combinatorial materials science is an emerging area which will enable the advanced materials discovery process to be markedly sped up[70]. This area has potential for a large user base and infrastructure to support it should be considered. It will be particularly important to integrate the use of informatics into the design of such infrastructure to maximise the utility of the large data sets being produced.

Heavy ion accelerator science

Current heavy ion accelerator facilities contribute to various research areas, including nuclear physics, materials research and characterisation, as well as a broad range of cross-disciplinary research, for example radiocarbon dating and soil analysis.

The Characterisation capability could be expanded to include the characterisation components of heavy ion accelerators. This would involve support for the development and operation of beamlines and end stations for ion beam analysis of materials.

Ion accelerator facilities are also included in the Fabrication capability area.

69 www.ansto.gov.au/discovering_ansto/publications_audio_video_and_images/publications/corporate_plan_2010-2015
70 An example is the National Institute of Standards and Technology Combinatorial Methods Centre in Maryland, USA www.nist.gov/mml/polymers/combi.cfm

FABRICATION

DESCRIPTION

The ability to synthesise advanced materials, fabricate device components and produce prototypes is vital to increasing the innovation dividend from Australia's investment in basic materials research, solving problems in diverse research areas, and progressing research outcomes to market through engagement between industry and the research community.

Facilities for nano, micro and macro fabrication are required to enable researchers to understand the structures and properties of new classes of materials, progress technology development and demonstration of products and processes, integrate and package components for a wide range of devices and provide new commercial products.

The Fabrication capability is fundamental to pervasive, cross-cutting research challenges as it supports research in a variety of areas, such as defence, medical and biological disciplines.

STRATEGIC IMPACT

Image 0

Nano, micro and macro scale fabrication infrastructure provides researchers with the tools necessary to advance technologies that contribute to improved health, safety and communication, for example.

The integration of fabrication solutions offers great potential to further leverage Australian research strengths. For example, the interaction between biology and soft matter with traditional inorganic hard matter device technologies will underpin applications in bionics, sensors, plastic electronics and drug delivery. The fabrication of quantum/nano scale photonic, electronic and electromechanical structures, and nanoparticulates, will have a major impact on all areas of ICT and sustainable energy technologies, as well as defence and security systems.

Nanotechnology in photonics, electronics, bioplatforms and microelectromechanical systems research remains a priority, with massive growth predicted in these areas.

Significant impacts can also be anticipated from the use of advanced fabrication infrastructure, for example in metamaterials, high temperature materials, photovoltaics, robotics, bioengineering, biomaterials, sustainable energy technologies, hybrid materials, multi-material optical fibres, integrated nanophotonics, micro and nanofluidics, surface engineering and functionalised nanoparticles, nanolayers, nanotubes and nanowires.

Fabrication enables the linking of engineering and biomedical sciences, including biomedical devices and biomimetics. Basic research in the applied science and engineering areas of quantum computing, quantum and quantum-atom optics will also be supported by an enhanced Fabrication capability.

CHALLENGES AND ASSUMPTIONS

To expand and enhance research outcomes in the Fabrication capability, researchers require access to local, well coordinated, integrated, state-of-the-art facilities, supported by expert technical staff. These facilities should comprise the full research product value chain, from advanced materials design to materials synthesis, through to the processing of devices to packaged prototypes.

The virtual laboratory is likely to become an enabler in the future: integrating people, projects, data, instrumentation, interpretation tools and publishing in a unified virtual environment.

The inherently different requirements of academic and industry researchers should be balanced in this capability by considering the flexibility of fabrication tools, industry readiness and the need for reproducible and reliable processes and quality control.

There is an opportunity for greater interaction to obtain synergies across existing capabilities. For example, state-of-the-art characterisation capabilities are critical to the fabrication of devices and materials. Successful collaborations should be built upon into the future. Facilities should also be encouraged to broaden their user base, for example through increased visibility in the research community.

An increased focus on integrated, cross-disciplinary research in areas such as nanotechnology, photonics and biotechnology warrants consideration of the benefits and opportunities that may arise through co-location of certain fabrication facilities with characterisation, health discovery and translation, sustainable energy, and defence and security facilities. This will enhance cross-disciplinary collaboration, reveal new areas for investigation and encourage the development of industrial applications. In addition to strong linkages and interaction with the Characterisation capability, this capability area supports many others, such as Sustainable Energy, Translating Health Research, Astronomy, Space Science and the environmental capabilities.

Upcoming engineering challenges, such as the effects of climate change in urban environments, present the need for the development and enhancement of novel methods of fabrication, materials development and engineering processes.

SPECIFIC REQUIREMENTS

Continued support for existing fabrication facilities is a priority. Ongoing support for device fabrication and synthesis is needed to ensure core facilities remain state-of-the-art. In addition, the alignment and/or grouping of downstream facility chains and related capabilities should be considered. Ongoing replacement of tools will be required along with investment in new equipment.

Research facilities should include cutting-edge equipment housed in cleanrooms, and expert personnel, that provide the capability to design, engineer, fabricate, process, manipulate, synthesise and integrate advanced materials (including biomaterials) and devices.

A key area that has been identified as requiring attention is the current gap in Australia's research capabilities related to the design and synthesis of advanced materials and quantum/nano structures. In particular, breakthrough science, innovation, platform technologies and intellectual property generation related to devices are increasingly embedded within the design and growth of advanced materials and nanostructures, rather than in the subsequent device fabrication and processing technology. Australia requires facilities for state-of-the-art design, growth and deposition of advanced materials and quantum/nano structures. Priority consideration should be given for this enabling and high impact research capability.

Research outcomes will be strengthened if researchers can design, engineer, model, predict and test while manufacturing and packaging prototypes for physical evaluation. Equipment to enable the development and realisation of rapid and complex prototypes will accelerate fabrication research into development and commercialisation, along with experimental testing of concepts with rapid feedback for iterative development. Novel manufacturing techniques such as 3D printing and 3D material structuring should also be considered.

Prototype fabrication facilities are a gap in current research infrastructure. Advanced materials design and synthesis, sensors and measurement systems, and fabrication, for example, need to converge to provide new prototypes and commercial products. Investment in packaging and back-end fabrication techniques and larger scale metrology facilities will streamline progress to market for innovative materials. The delivery of fully functional, packaged devices and prototypes requires not only versatile equipment platforms but also new expertise. Packaging across multiple length scales is required to enable nano and micro device technologies to interface with real world systems.

Ion implantation and ion accelerator infrastructure remain a priority, noting that this is also relevant to the Characterisation capability. Specific support for capital investment in beamline instrumentation should be considered under the Fabrication capability area. For example, there is a need for development and operation of beamlines, end stations associated with ion implantation and associated ion beam processing.

Support for researchers to access and navigate existing and future facilities is an additional priority. The provision of expert advice to researchers and strengthening of concept and design capacity by coordinating activities across several facilities (in particular in characterisation and fabrication) is necessary to capitalise on earlier and any future investments. This may include the expansion of skills in the current facilities and exchange of personnel and expertise.

Definition of advanced materials

Advanced materials are materials which, as a result of innovative design, synthesis, fabrication or processing techniques, acquire novel structures or superior properties. There is high demand for materials with step change improvements in performance to meet major needs in areas such as health, transport, energy, natural and built environments, communication and defence.

Next generation materials will be multifunctional (for example, biomedical materials that combine targeted drug delivery and medical imaging agents or stem cells and functionalised scaffolds), adaptive (for example, being able to self-heal when damaged) and smart (for example, being able to monitor corrosion or strain).

EXAMPLE

SENSORS AND INSTRUMENTATION – NEED FOR AN INTEGRATED APPROACH

Recent advances in sensors and sensor networks have opened up new approaches to probing our world, and to making decisions based on information gained in real time. There is also an increasing desire for smart technologies to monitor our health, the environment and industrial processes, as well as for defence and security. In addition, Australia has a long-standing reputation internationally for excellence in instrumentation and the application of new technologies, most particularly in areas such as astronomy and biotechnology.

We are living in an era of biology-chemistry-physics-engineering convergence and it is anticipated that many future advances will occur at the interfaces between these disciplines.

For Australia to secure a leading reputation in new sensors, sensor networks and advanced instrumentation in these converging areas, it must build on established research strengths in materials science, photonics, experimental physics, biotechnology and engineering.

Infrastructure is needed to support research that brings together emerging materials systems and fabrication technologies to create new forms of sensing devices capable of measuring the chemical, biological or physical characteristics of systems at scales ranging from single molecules to entire ecosystems. Such devices will increasingly need to be capable of multiplexed sensing, of working in real time to facilitate decision making, and of being integrated with other sensing modalities and high-throughput techniques.

In order to secure advancements in this vital area, the Fabrication and Characterisation capability areas should be built upon to ensure the necessary infrastructure is provided to support sensors, sensor networks and instrumentation development.

Many of the research infrastructure capability areas across this Roadmap are dependent on advances in sensors, sensor networks and instrumentation. For instance:

- The environmental capabilities rely on the use of sensor networks for sustained observations of the critical components of the Earth's systems.
- Advanced instrumentation is vital for securing Australia a significant role in big science projects, particularly in astronomy and space science.
- The use of sensors for medical monitoring applications is an emerging and vital area, particularly in the move to more personalised medicine.
- The development of adaptations and extensions to the suite of 'omics technologies in the Integrated Biological Discovery capability.

Research in sensing and measurement systems offers particular opportunities to achieve broad ranging outcomes across research priorities as well as strong industry engagement.

SPACE SCIENCE

DESCRIPTION

Space science addresses the properties, dynamics and evolution of the solar system and humankind's place in it, from the Sun to the Earth's ozone layer, and into the local interstellar medium.

Space science is an underpinning capability for a range of other research disciplines. Data returned by Earth Observation Systems (EOS) and Global Navigation Satellite Systems (GNSS) are utilised in a variety of scientific, engineering, commercial and service contexts, including geology, geophysics, environmental, atmospheric, marine and climate science, natural resource management, defence and national security.

Space science is a platform for scientific discovery in its own right, in areas such as planetary evolution and the development of life. It also has particular importance for modern human activities because space phenomena, such as solar activity, influence numerous Earth system processes and have the capacity to affect the operation of significant infrastructure such as national power grids, communications and satellite systems.

STRATEGIC IMPACT

Image P

Australia's favourable geographic location and large geophysical footprint, with United Nations responsibility for approximately one eighth of the surface of the globe, provides advantages for space science. This makes Australia well suited for studies of the Sun, Earth and solar system, for monitoring space weather and for tracking and communicating with a large number of the world's satellite systems.

Observations of the Earth from space, including Australia's participation in the Global Earth Observation System of Systems (GEOSS), are an important and rich source of information that supports many of the capabilities outlined in this Roadmap. Data from EOS contributes to predicting global weather, studying climate, and managing water availability and energy resources. The data also assists in understanding agricultural and urban impacts, mitigating natural disasters, protecting terrestrial, coastal and ocean ecosystems, and monitoring biodiversity.

Augmentation and upgrades to Australia's networks of terrestrial GNSS stations will enable far more precise spatial positioning and geodesy, opening up a range of new and innovative applications with major benefits for both science and industrial productivity. In particular, GNSS-enabled machine automation will deliver important economic benefits to the agricultural, construction, transport and mining sectors.

Data and services from space-based platforms and ground-based observatories are building our understanding of the dynamics of the Sun's interactions with communications systems, and the geospatial and geochemical structure of the Earth.

Continued development of domestic space-borne instrumentation and data acquisition systems, as well as augmentation of ground-based support infrastructure for EOS and GNSS, will allow Australia to assure ongoing access to critical space-enabled services. This will enhance Australia's standing as a contributing and influential partner in international space science consortia.

CHALLENGES AND ASSUMPTIONS

An enhanced space capability will address an important layer in Australia's national research infrastructure, between Earth science and astronomy, by building upon existing investments in these fields. It is important that any investment in research infrastructure to support space science takes into account the broader space related activities of the Australian Government[71].

Australia will continue to rely on data received from international space systems for its diverse and growing EOS needs, but Australia's future access to 'free to ground' satellite imagery and sensor data cannot be taken for granted. Australia therefore needs to identify and secure appropriate access arrangements to new satellite data sources that meet national needs, and engage further with global partnerships to transfer the benefits of EOS science and technology to the community[72]. Ensuring that necessary supporting communication services, which transfer the data and information received to ends users in a timely manner, is also important in supporting this capability area.

Australia must make best use of its geographic and other comparative advantages as a location for ground station facilities to provide calibration and validation (CALVAL) services for satellite systems, and build on the respect it has achieved through international space science collaboration.

Infrastructure investments that support international collaborations in EOS, GNSS and space technology will allow Australia's research sector to continue to contribute to, influence the operations of, and benefit from ongoing access to international space systems. These investments include space-borne and ground-based instrumentation, launch vehicle and satellite propulsion systems and new GNSS receiver and software systems. There is no strong case to support Australia developing an indigenous launch capability.

Clearly the Astronomy and Space Science capability areas are complementary and there is scope for synergies and mutually beneficial research infrastructure which need to be considered as part of any future investment.

71 www.space.gov.au/Pages/default.aspx
72 www.science.org.au/reports/documents/EOSfinal.pdf

A wide range of other capabilities in this Roadmap will benefit from enhanced space science capacity, in particular the environmental capabilities, Integrated Biosecurity and Biological Collections and Biobanks capabilities.

The Space Science capability in its turn is also reliant on the continued development of advanced materials, sensors, sensor networks, ground-based and space-borne instrumentation, which are all supported through the Fabrication and Characterisation capabilities.

SPECIFIC REQUIREMENTS

To maximise the benefits of the science of space and science from space, Australia's space and Earth science disciplines will benefit from access to individual and networked ground-based sensors, radars and satellite receivers, satellite ranging systems, communications terminals and networks, image processing software, and a variety of small near-Earth satellites.

The *Decadal Plan for Australian Space Science 2010-2019*[73] by the National Committee for Space Science should be referred to when considering specific investments.

A successful EOS outcome depends on Australia renewing and upgrading its ground-based reception infrastructure to handle the volume and variety of data that will become available to the research community from new generations of imaging and remote sensing satellites.

Space scientists and researchers who rely upon Earth observation and position, navigation and timing would benefit greatly from integration of EOS and GNSS application and eResearch infrastructure. This should include access to international EOS, spatial and remote sensing data archives. Such integration would enable close-to-real-time fusion and assimilation of multiple space data streams into theoretical models, and feed into global Earth and space monitoring systems.

Strategic deployment of ground and space-based infrastructure, including test beds and access to continuously operating reference stations (CORS) to access multiple international GNSS signals, will enable Australia to contribute significantly to global geodesy projects, with significant long-term benefits for the nation's research sector and economy.

Australia's international participation in space science would be advanced by developing space technology including new radar and integrated photonics instruments as well as high performance computing and software for space technology simulation. The sector also requires laboratory test and development facilities, for example to progress the development of satellite instrumentation, plasma thrusters and hypersonics, in particular scramjets and high thermal-load materials.

The space science sector also requires government support in the national coordination of civil space use, managed access to suitable radio frequency spectrum and participation in international regulatory frameworks, treaties and protocols that support Australia's use of space. Australia's growing dependence on major international space systems will require new government-to-government arrangements, as well as programs and services to enable Australia's institutions and companies to contribute materially to international infrastructure and global collaborative projects.

73 www.science.org.au/natcoms/nc-space/documents/nc-space-decadal-plan.pdf

DIGITISATION INFRASTRUCTURE

DESCRIPTION

A Digitisation Infrastructure capability is required to build Australia's capacity to enable large collections of artefacts, images, sound recordings, documents, films, animals, insects, plants and geological samples to be accessible in digitised form.

Many collections of national and international significance in the natural sciences, humanities, arts and social sciences are currently available only to researchers who can physically visit their repositories.

A Digitisation Infrastructure capability will be implemented by assembling state-of-the-art digitisation technology and expertise to provide high-throughput digitisation services to the Australian research community to achieve priority research outcomes.

This will capitalise on Australia's investments in eResearch infrastructure to ensure maximum use of Australia's invaluable collections, providing access for remote, regional and global communities and new opportunities for diverse research disciplines.

STRATEGIC IMPACT

The range of disciplines that would benefit from this capability is vast, including biology, environmental science, ecology, zoology, geology, humanities, arts, social science and health sciences. Australia's curators, statisticians, scientists and communities would all interact with this capability.

By enabling greater access to research resources, important research questions will be able to be investigated. Research collections are preserved for use within their original discipline but sometimes their greatest impact can be in another field of research. For example, the availability of digital information from diverse anthropological collections is being used for research into agriculture, biomedicine, control of invasive species and other fields.

Virtual connections between institutions, collections, and communities will enhance interdisciplinary collaborations through shared creation of digital data and access to the latest instrumentation. Access to digitised and connected collections will have many time and cost benefits for researchers, leading to significant productivity gains.

The capability area will also address the urgent issue of the preservation of research material that is known to deteriorate over time. Collections of natural materials such as insects, flora and fauna as well as magnetic tapes, printed documents, artefacts, film and microfilm are inherently prone to damage and decay. There is limited time before these materials become unusable. Appropriately managed and curated digitisation prevents this loss and transforms these research sources into a permanent and durable form.

Digitisation of Australian collections will help ensure that Australian data is incorporated into international studies, influencing both the questions asked and the solutions that are generated. For Australian researchers, increased access to Australian datasets will result in findings which directly reflect Australian situations.

Digitisation will also allow dispersed collections to be studied as a whole.

This capability will increase the scope and reach of Australian research by enabling collections to be discoverable. As well as revolutionising the access to this material by researchers, it will be valuable to the community at large, including citizen scholars. Once digitised, a collection is available to be enhanced, connected and enriched by the wider community.

The capability will augment existing dispersed and incomplete digitised data sets and will promote greater collaboration between many of the capabilities identified in the 2011 Roadmap.

Furthermore, the Digitisation Infrastructure capability will exploit the potential of the broader digital revolution and Australia's investment in eResearch infrastructure.

CHALLENGES AND ASSUMPTIONS

The digitisation of collections is only of benefit if there are structures in place for storing, curating, accessing and analysing the resulting data. This requirement will depend heavily on ongoing support for eResearch infrastructure programs. Current eResearch infrastructure projects, as well as future projects which may be implemented under the Cultures and Communities capability will be critical to the Digitisation Infrastructure capability. In addition, the implementation of this capability must build on already implemented digitisation projects and digital collections, consolidating previous work and bringing all to a shared standard.

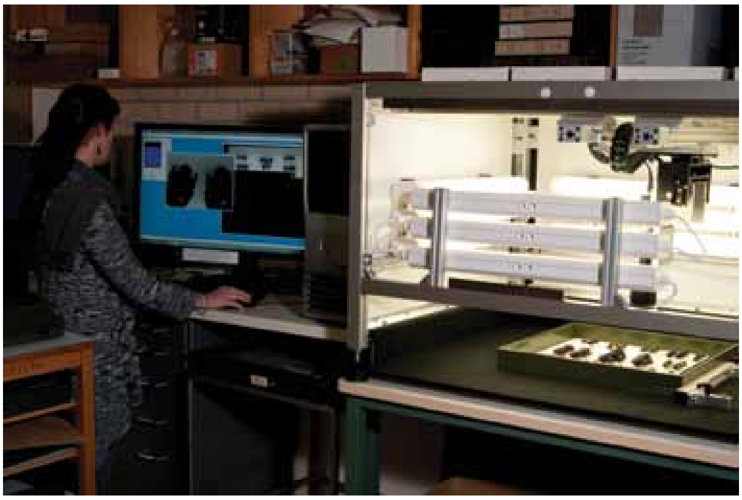


Image Q

Appropriate standards for data and digital record creation and management are necessary to ensure that the Digitisation Infrastructure capability can service the needs of the research sector today and in the future. This capability will need to be consistent with the principles concerning data raised in the introduction.

The vast array of collection material and the level of demand for digitisation services will be a challenge in implementing this capability. Extensive consultation with the research community and collection holders will be required to ensure priority is given to the digitisation of collections that are of national and international research significance or are necessary to answer nationally significant research questions.

In addition, issues of access, privacy, intellectual property and copyright surrounding some of the data made available through digitisation will be a challenge. It is anticipated that the majority of digitised collection data would be publicly available as this provides the maximum benefit to the research and general communities. A number of initiatives, such as the National Library of Australia's *Trove* project[74] and the Council of Australasian Museum Directors and Museums Australia's *Museum Metadata Exchange* project[75], have developed some innovative approaches to these issues which could be drawn on in implementing this capability.

Extensive stakeholder consultation will be needed to ensure optimal selection of technologies, to develop a merit based process to prioritise collections and to ensure integration with various collection institutions

Research into digital preservation and associated infrastructure is an evolving field but fundamental to the successful implementation of a Digitisation Infrastructure capability. Developments in this field will need to be considered in the establishment of the capability to ensure it is able to service the research sector in the future.

Any Digitisation Infrastructure capability will need to consider existing digitised datasets and develop strong linkages to other capabilities, particularly those of Cultures and Communities, Biological Collections and Biobanks, as well as eResearch Infrastructure.

SPECIFIC REQUIREMENTS

The digitisation technology will need to be chosen to suit the highly varied demands of the user community and types of material to be digitised. Technology may include equipment suited to mass digitisation of objects, automated digitisation of audio-visual recorded material or microfilm, automated equipment suited to paper-based/archival collections, and technology suited to high-throughput processing of organic herbarium and natural history specimens, including those at microscopic scale.

3D technology for both imaging and rendering is anticipated to be routinely used in the near future and scanning of objects using a variety of imaging technologies is becoming increasingly common. Mobile digitisation technology is likely to become important as it can be taken to fragile unmoveable and regional collections as well as allowing for digitisation of objects as found.

Research infrastructure for this capability area will take advantage of newly developed rapid digitisation technology suited to large scale or mass digitisation. These tools will transform the traditional, labour intensive processes previously required to make digital data available.

In order to serve the broadest range of users, a distributed facility model should be considered. This may include a suite of services, not just the instruments, but also the provision of expertise on techniques, methodology and interpretation.

74 http://trove.nla.gov.au/
75 www.museumsaustralia.org.au/site/mme.php

eRESEARCH INFRASTRUCTURE

DESCRIPTION

eResearch infrastructure comprises the information and communications technology (ICT) assets, facilities and services which support research within institutions and across national innovation systems and which contribute to the capacity of researchers to undertake excellent research and deliver innovation outcomes. eResearch infrastructure increases both the efficiency and effectiveness of research and opens up new and innovative research possibilities, across all disciplines including the ability to disseminate that knowledge. This reflects the fact that eResearch infrastructure is an integral part of modern research.

Planning for future eResearch infrastructure builds on the near ubiquitous deployment of high bandwidth research networks; on investments in, and excellent uptake of, high performance computing; and growing understanding and uptake of data management practices. The impact of collaboration tools and resources is being reinforced while the use of authorisation services is well established and growing.

STRATEGIC IMPACT

Some of the key advances arising from investment in eResearch infrastructure include global competitiveness in research, productivity driven by efficiencies and effective use, faster processing and deeper collaboration, discoveries that were previously unfathomable, and the ability to grapple intelligently with vast amounts of research data.

The rapid transformation of research by ICT-based research infrastructure has shifted from a focus on early adopters to an almost ubiquitous experience at all levels of research. This has been supported by longer term investment in eResearch infrastructure which has resulted in the establishment of eResearch foundations across the country, through national and state-based initiatives.

eResearch infrastructure supports the ability to conduct research in more efficient, seamless and connected ways, from a greatly enhanced information base. There is also the potential to stimulate economic growth through research gains in industry and in attracting international researchers, research organisations and international facilities to Australia.

Ensuring the international significance of Australia's contribution to research relies on our ability to harness the tools that make data meaningful to the researcher, the user and the policy maker[76]. Our ongoing ability to lead the world and make unique and major contributions to key research areas will rely on continued investment in eResearch infrastructure.

76 For example, in a digital age, developments in eResearch infrastructure complement broader initiatives, such as the National Broadband Network and the Australian Government's development of a *Strategic Vision for the Australian Government's use of ICT*. In particular, research productivity enabled by ICT is matched by gains in research-related outcomes

CHALLENGES AND ASSUMPTIONS

The need for appropriately secure, open and user-friendly access to eResearch infrastructure will accelerate over the next five to ten years. Researchers will need to be enabled to manage their own collaborative research environment, in which they will be able to move seamlessly from and between desktop computing, mobile technologies, particularly hand held devices, high performance computing and cloud computing.

The rate of data growth, including data produced from scientific instruments, streaming and mobile devices and digitised information, has the potential to outstrip reductions in storage costs. The scale of data storage required now and into the future, particularly as open access to research data increases, has implications for funding continuity and the need for data management infrastructure.

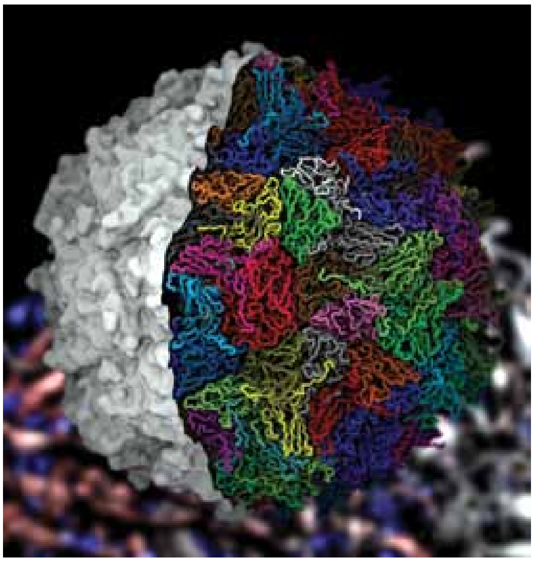


Image R

The huge opportunity presented by data integration, re-use, mining, analysis and visualisation compounds these trends as will the need to manage the links between data and publications (and in some cases computation models).

eResearch infrastructure will need to be flexible so that future technologies can be easily integrated. Cloud computing and mobile technologies will continue to evolve and will increasingly allow researchers to connect to their experiments, data and analysis tools from anywhere at any time.

In some disciplines, the trend towards cloud computing and large scale international experiments will have implications for access to overseas facilities. These developments will increase the demand for enhanced international connectivity, research services and data networks, and for solutions to sovereignty and privacy issues. Issues associated with interoperability between public and private clouds will also need to be addressed.

Balancing support for high end users while also providing the infrastructure that will lift the participation of the many disciplines that are relatively late adopters of eResearch is another challenge. There is now significant acceptance that both a foundational eResearch infrastructure base and eResearch solutions designed for specific domains are required.

It will be critical to balance support across the specific high end computational needs of some disciplines (such as discipline or demand driven research, for example high performance computing for climate science) and the needs of a wider range of researchers including access to more generic but similarly transformational eResearch infrastructure (such as collaboration tools, data, software, networks and/or compute).

eResearch infrastructure provides a critical foundational component for many of the other infrastructure areas outlined in this Roadmap. Meeting these challenges is necessary to ensure that the impact of eResearch is felt across the research sector including between and within individual research disciplines.

REQUIREMENTS

BROAD REQUIREMENTS

In framing the path ahead for continued investment in eResearch infrastructure, it will be essential to ensure that both existing and new eResearch infrastructure can interconnect with each other and across capabilities in ways that bring about highly developed solutions and support research excellence in meaningful ways. The next stage of implementation must:

1. ensure the investment framework is flexible enough to support new and emerging priority areas, respond to advances in technology and provide a responsive balance between capital and operating infrastructure investment
2. build stronger coordination and ensure that national investments continue to complement and support the development of state and territory and institution based eResearch capabilities as well as the integration of the services provided by external eResearch providers including industry
3. enable a deep integration of eResearch across Australia's research community, including the need for enhanced support to build skills capacity.

There is a clear requirement for a coordinating component in eResearch infrastructure development and implementation. Efforts to increase coordination and collaboration, build economies of scale and reduce fragmentation will assist to ensure that the benefits delivered by eResearch are delivered across the research sector, and consolidated and maintained in the longer term. Underpinning principles for coordination could include:

- enabling communication and engagement between researchers, projects and programs, industry, institutions and agencies engaged in accessing and supporting eResearch and eResearch infrastructure, including building eResearch infrastructure visions and plans together
- coordination around important issues such as policy, research community and institution engagement, interoperability and implementation phasing and approaches. This could include supporting the development of data management planning for publicly funded research.
- extending and complementing ICT and eResearch support in institutions and by state and territory governments; including allowing for the evolution and migration of services over time from within institutions to external service providers, or from research budgets to organisational ICT budgets
- clearly identifying roles and articulating the space where investment should continue, and where other methods of providing eResearch infrastructure capability should emerge
- raise awareness of eResearch across many disciplines. This will be fundamental to capturing the significant benefit of existing and new investments.

While some researchers advance readily into an eResearch-enabled world, it is important to assist other researchers to better appreciate the benefits and to engage with eResearch infrastructure. The reality is that many researchers wish to benefit from a seamless experience of eResearch infrastructure without necessarily knowing how the infrastructure works.

A critical issue is the need to simplify and integrate the interface between the researcher and the eResearch infrastructure. It is also important for the interface between eResearch infrastructure investments to be easily accessible and useable, irrespective of how many individual initiatives or programs underpin the service, and in a way that supports a seamless balance between vertical (discipline or demand driven research) and horizontal requirements (data, software and/or compute).

In a specific discipline, such as astronomy, it is important to be able to move vertically to access data management, software, various compute and networking requirements without having to work with different horizontal initiatives. Vertical integration of services for targeted research communities is an emerging reality.

Equally, it is critical to ensure horizontal integration and management, for example a cross-discipline capability in data management which can respond to the needs of individual researchers allowing new research that previously could never have been envisaged.

Ultimately, the aim should be to coordinate and position eResearch initiatives to provide broad, deep and well integrated support to the researcher that facilitates a seamless interaction between institutional resources, national eResearch infrastructure initiatives and the services delivered by other eResearch providers including industry.

SPECIFIC REQUIREMENTS

The following specific requirements recognise that the investments currently in place must be built on and, as appropriate, extended to support further advances.

Data

Australia's ongoing research success will depend on the development and improved management of national and global research data environments, as well as the engagement of researchers and research institutions in improving and supporting data management initiatives.

The significant increase in the rate of data being captured, the range of disciplines and capability areas depending on data and the substantial potential benefit offered by integrated data analysis and re-use require more coordination across initiatives and between stakeholders.

eResearch infrastructure investments to date have made important headway towards addressing data management, data sharing, access and availability across and between research institutions, including dealing with issues associated with data capture, aggregation, transmission, storage, access, re-use and curation. The significance and importance of data have also been recognised throughout the 2011 Roadmap.

Recent initiatives have positioned Australia well globally, but we need to move towards a national research data management framework, supported by strong data management leadership, that links data, publications and related information. The framework should include consideration of integration with international approaches to research data and must include:

- an holistic approach towards the creation, integration, management and storage of research data repositories as part of the broader national scholarly information infrastructure, including common data access and data movement infrastructure that is open to both the producers and consumers of research data
- guidelines to deal with issues related to policy, ethics, ownership, access and discovery, privacy and security

- access to research significant data collected and held outside research institutions, for example, by the Australian Bureau of Statistics, the Australian Institute of Health and Welfare and the National Archives of Australia
- coordination of appropriate access to both research and administrative data sets, including the development of standards and agreed protocols and schema
- consideration of including a requirement for data management plans and embedding the data management framework into funding grant rules
- the development and use of research tools, particularly in the areas of automated metadata, access, data movement, data linking, analysis, visualisation and data mining techniques; all of which will further the aim of data re-use
- recognition of and support for the links between data and publication, and in some cases computational models or other tools.

In addition, the support of institutions is needed to:

- put in place automated metadata capture and data publication frameworks
- facilitate the export of data to repositories and between institutions and data intensive facilities.

It will be critical in developing a national research data management framework to recognise the foundational role of existing eResearch infrastructure investments, in particular in data management and data storage. The sector will need to coordinate and, where necessary, require and reward the necessary changes in practice. An aspirational aim could be to ensure that by 2020 all appropriate data will be captured and discoverable at the time of creation and that initiatives will be well advanced to deal with already existing data sets, collections and publications.

In addition, to maximise benefits of any future initiatives undertaken by the Digitisation Infrastructure capability, it will be essential to align them with the proposed research data management framework.

High performance computing

Demand for national high performance computing (HPC) infrastructure, which underpins problem solving methodologies across a broad range of research domains, continues to grow at significant pace. Globally, this can be seen in moves towards exascale approaches to computing. To support HPC infrastructure while preparing for exascale computing, Australia requires:

- continuing investment in consolidated peak HPC capability
- specialised computational support to find solutions to challenges such as achieving close coupling with unique digital instrumentation, data collections and integration of unique computational methods
- development of scaled hardware
- flexibility to buy processing capability from commercial cloud service providers, where appropriate
- support for the 'new breed' of computational experts required to support the transition towards exascale computing
- specialist HPC facilities for particular research communities, where there is genuine national need. However, these should not be developed independently of investment in consolidated peak HPC capability.

A strategic assessment will be required to determine if Australia should develop its own exascale capacity or consider collaborating internationally to enable access to such a capacity for Australian researchers. However, a continued strong onshore infrastructure presence is necessary if Australia is to develop and retain the expertise that is critical to advances in computational science and HPC.

Support for ongoing human capacity and expertise in HPC is a critical component and includes expertise in peak services as well as allowing national capabilities to become comprehensive service providers of high end services.

Investment centred on data centric computing rather than compute centric capacity is also an important consideration. Data intensive workloads are the new paradigm in technical computing, driven by exponential data volume growth from all kinds of sources, such as telescopes, satellites and high-resolution scientific instruments. Other requirements could include the following:

- Simulation software which might include large complex suites of software codes and libraries. Software codes, which are often discipline specific, could be accessed in the same way as international research infrastructure. A case may exist for their purchase to be considered as part of infrastructure investment, where they come with substantial recurring costs.
- Visualisation is required for most scientific and other disciplines using computational or data resources. With larger and more complex simulations and data sets, visualisation will continue to be the essential user interface to extract results and insights.
- Some computational codes and data sets being created are now of a scale to be considered infrastructure in the same sense that a telescope or research vessel is infrastructure.

Software, tools and collaboration resources

Software, tools and collaboration resources enable researchers to access, annotate and analyse large scale, distributed datasets, as well as to ingest, manage, annotate, analyse, share and publish their own data. To allow effective collaboration it will be critical that many of these software tools are standardised and effectively managed.

Shared online spaces empower researchers to work with each other and more easily share and access global resources, including through software, common tools, web and video collaboration. In addition, shared collaboration spaces enable researchers to use simple, customised user interfaces to perform large scale simulation, modelling and analysis on high end computing facilities; perform complex workflows that automate tasks currently done manually; and remotely manage and operate facilities, instruments and sensor networks.

A number of related issues will need increasing attention:

- continued promotion and ubiquitous adoption of authorisation and authentication measures, underpinned by single sign-on approaches. While significant advances have been made in this space, the reach of such measures needs to extend to holders or providers of data relevant to research beyond public research organisations, such as government and commercial eResearch service providers
- more sophisticated software and tools will need to be developed, deployed and standardised to enable data analysis, modelling, mining, simulation and high-resolution visualisation. As data sets increase in size, having tools that can effectively merge or enable researchers to work across the data sets will become increasingly important
- development should continue in a mixture of both case specific and general eResearch infrastructure tools, software, services and resources, including making them ready for exascale computing.

Many tools are available internationally or commercially, and serious consideration should be given to accessing these where possible.

Where data understanding or interpretation is contingent upon software, it will be critical to build sustainability into the software development process. Software creation is a discipline, as is data curation, and the development of software and tools must:

- adhere to industry standards and architectures to avoid duplication and ensure re-use and interoperability
- integrate into national mechanisms which allow sharing of software and tools, such as an 'apps store' to enable researchers to work directly with multiple data sets as a user, and which foster software skills development
- seek to develop metadata around software, as well as data, so that it is discoverable
- recognise that researchers also require skills to use the software
- embed collaboration tools, software and resources into routine activities of researchers.

Networks

The Australian Research and Education Network (AREN) is an advanced research and education network that connects universities and research institutes in all capital cities, many regional centres and isolated research facilities such as radio telescopes, as well as connecting Australian researchers to international collaborators.

A comprehensive, cooperative and non-competitive approach to network strategy, operations and capacity planning is essential. In order to facilitate this, AREN providers[77] must collaborate to deliver interoperability and interconnection between their respective networks.

Future strategic development of the AREN should focus on:

- continued extension of the reach, redundancy and scalable capacity of the national backbone with a priority focus on known and anticipated research demand
- provision of higher level overlay networks for specific research communities to support the development of higher order applications and services
- enhanced international network capacity, including high quality eastern and western seaboard access to ensure redundancy
- greater interoperation between AREN service providers and commercial networks, including the integration of broadband wireless research and data collection sensor networks into the core network
- enhanced connection of researchers and a range of public and private research organisations to the AREN, including access to the resources held in these institutions that can be shared for research use.

To underpin large science initiatives, leverage existing investments and build on the capability of multiple service providers, future investment must, wherever possible, engage both network infrastructure providers to the AREN and to broader network initiatives in Australia.

At all times the use of existing network infrastructure investments should be optimised with the expectation that network partners will collaborate to ensure new networks are not built where current capacity exists. New funds can then be directed to the creation of special services where service provider capabilities are not otherwise available.

eResearch infrastructure needs of capability areas

Collaboration and coordination of eResearch infrastructure will optimise the ability to effectively meet the specific eResearch infrastructure needs of the capabilities.

An initial map of the likely national scale eResearch infrastructure requirements of the capability areas has been provided on the next page. It indicates where these requirements intersect with the current eResearch infrastructure investments in the areas of: data; high performance computing; software, tools, collaboration resources; and networks.

77 These include AARNet, VERNet and SABRENet

Table 2 – The anticipated national scale eResearch infrastructure requirements relating to each of the 2011 Roadmap capability areas

eResearch Infrastructure	Data			High Performance Computing			Software, Tools and Collaboration Resources			Networks	
	Management	Storage	Sharing	Model	Visualise	Analyse	Research Tools	Virtual Labs	Cloud	Bandwidth	Reach
Marine Environment	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
Terrestrial Systems	✓	✓ ✓	✓	✓ ✓	✓ ✓	✓	✓	✓	✓	✓ ✓	✓
Atmospheric Observations	✓	✓	✓	✓	✓	✓	✓			✓	✓
Solid Earth	✓	✓	✓	✓ ✓	✓	✓	✓	✓	✓	✓ ✓	✓
Urban Settlements	✓	✓	✓	✓	✓	✓	✓ ✓	✓	✓	✓	✓ ✓
Sustainable Energy	✓	✓	✓	✓	✓		✓			✓	✓
Integrated Biosecurity	✓	✓	✓	✓	✓	✓ ✓	✓	✓	✓	✓	✓ ✓
Cyber Security	✓	✓	✓		✓	✓	✓			✓	✓
Astronomy	✓	✓ ✓	✓	✓	✓	✓ ✓	✓			✓ ✓	✓
Population Health Research Platforms	✓	✓	✓		✓	✓	✓ ✓	✓		✓	✓
Translating Health Research	✓	✓	✓				✓			✓	✓ ✓
Cultures and Communities	✓ ✓	✓	✓ ✓		✓	✓	✓ ✓		✓	✓	✓ ✓
Integrated Biological Discovery	✓	✓ ✓	✓ ✓	✓ ✓	✓	✓ ✓	✓ ✓	✓	✓	✓ ✓	✓
Biological Collections and Biobanks	✓	✓	✓ ✓				✓	✓		✓	✓ ✓
Characterisation	✓	✓ ✓	✓	✓	✓ ✓		✓	✓	✓	✓ ✓	✓
Fabrication	✓						✓	✓	✓	✓	✓
Space Science	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
Digitisation Infrastructure	✓	✓ ✓	✓ ✓			✓	✓		✓	✓	✓ ✓

LEGEND

✓ *Essential national eResearch infrastructure support is needed to underpin the research. Special / enhanced needs not yet identified if these exist.*

✓ ✓ *Essential and advanced national eResearch infrastructure support is needed to underpin the research. Special or enhanced needs are known.*

EXAMPLE

COMPUTATIONAL SCIENCE – NEED FOR AN INTEGRATED APPROACH

Computational science is a multidisciplinary field that uses advanced computing capabilities to understand and solve complex problems. It employs mathematical models and quantitative analysis techniques in computer simulations of problems in various research fields and in many it is recognised as a third route to discovery, sitting alongside experiment and theory.

Often events simulated in computations are too fast, small, large, complex or dangerous to be amenable to experimental investigation, such as the motions of molecules, economic processes or predictions of future climate. Simulation and modelling are also central to modern engineering practice. Computational engineering, for the design and optimisation of new products and processes, is now pervasive across technical and consumer products and major industrial and societal infrastructure.

The pace of technological developments in computer hardware has been unrelenting for decades. This can be expected to continue and will require energetic efforts to develop new algorithms and software to capture the performance of emerging hardware platforms. Surmounting these challenges will open up new performance horizons for researchers using computational methods, and ultimately enable new discoveries.

As a new era in algorithms and simulation codes begins, it is essential that Australia's next generation of researchers are provided with a path to the frontiers at which their international collaborators are working. Specifically there is a need for integrated hardware and software systems, algorithms, visualisation tools and computer code libraries to be provided in an integrated, coherent and generally accessible manner. This will need to be accompanied by appropriate training and educational programs. Most critical is a clear focus on research user needs and usability of the technologies.

The eResearch Infrastructure and Fabrication capability areas provide essential support for computational science. In turn, computational science supports many of the capabilities set out in this Roadmap, including Space Science, the bioinformatics and biostatistics aspects of Integrated Biological Discovery, Characterisation, and the environmental capabilities.

APPENDIX A

Australian Government
Department of Innovation
Industry, Science and Research

STRATEGIC FRAMEWORK FOR RESEARCH INFRASTRUCTURE INVESTMENT

NRIC NATIONAL RESEARCH INFRASTRUCTURE COUNCIL

Powering Ideas, the Australian Government's innovation agenda, aims to build a stronger national innovation system to assist in creating a better Australia – one that can meet the challenges and grasp the opportunities of the twenty first century.

Powering Ideas included the creation of the National Research Infrastructure Council (NRIC) to provide strategic advice on future research infrastructure investments.

The *Strategic Framework for Research Infrastructure Investment* has been developed by NRIC in consultation with the research sector to guide the development of policy advice and the design of programs related to the funding of research infrastructure. The Council will undertake stewardship, promotion and championing of the Framework across the Australian Government and the States and Territories.

Investment in innovation and research drives productivity. Excellent research infrastructure, addressing national priority areas, is necessary to deliver high quality research and innovation outcomes, to enable Australia to be globally competitive. The principles identified in this Strategic Framework will ensure that the approaches used to plan, fund and develop research infrastructure deliver the maximum contribution to economic development, social wellbeing, environmental sustainability and national prosperity.

PURPOSE OF THE STRATEGIC FRAMEWORK

The purpose of the Strategic Framework is to:

- identify principles to guide the development of policy advice and design of future programs related to the funding of research infrastructure;
- ensure that research infrastructure delivers the maximum outcome for the nation for the money invested; and
- improve consistency and coordination of Australian Government and State and Territory programs that support research infrastructure.

The applicability of the Strategic Framework principles will vary depending on the scale of the research infrastructure investment.

For the purpose of this Framework, investment in research infrastructure has been divided into three broad categories:

- Local – research infrastructure which could be expected to be owned and operated within a single institution.
- National – research infrastructure on a scale generally not appropriate to be owned or operated by a single institution and which often supports collaborative research and is generally regarded as part of the national research capability.
- Landmark – large scale facilities (which may be single-site or distributed) that serve large and diverse user communities, are generally regarded as part of the global research capability, and engage national and international collaborators in investment and access protocols.

DEFINITION OF RESEARCH INFRASTRUCTURE

Research infrastructure comprises the assets, facilities and services which support research across the innovation system and which maintain the capacity of researchers to undertake excellent research and deliver innovation outcomes.

PRINCIPLES FOR RESEARCH INFRASTRUCTURE INVESTMENT

Continuity of Funding

- Research infrastructure funding programs should be ongoing and predictable, to achieve optimal use of funds.
- Infrastructure that continues to be a priority should be able to access funding for ongoing operations.

Guiding considerations

- *Ongoing and predictable funding programs support a more strategic, collaborative and planned approach to research infrastructure investment.*
- *Ongoing operational funding for priority national and landmark research infrastructure assists in maximising the benefit from the original investment.*

Holistic Funding

- Funding required to support research infrastructure will vary between elements, including capital costs, governance, skilled technical support staff and operations and maintenance. Support should be available to cover these key elements.
- Funding programs should allow some funding for project development costs, either for a facilitation-based process or for project development and scoping activities.
- In the context where not all national and landmark infrastructure would necessarily be replaced, depreciation for these facilities should not be funded by Australian Government funding programs.

Guiding considerations

- *The ability to invest in human capital and operating costs results in superior service delivery and more efficient, productive and viable research infrastructure facilities.*
- *Funding for specialist staff assists in developing and maintaining the highly skilled workforce required for the efficient operation of sophisticated facilities.*
- *Rigorous, consultative project planning is a key input to developing excellent research infrastructure facilities, particularly at the national and landmark scale.*

Prioritisation

- Any proposed research infrastructure investment should align with and support Australia's research, innovation and infrastructure priorities.
- Funding for Australia's research infrastructure should focus on areas where Australia:
  - undertakes world-leading research or innovation;
  - has demonstrated a particular strength in international terms; or
  - has reasons to seek to strengthen capacity in an area of research or innovation.
- Prioritisation of investment in research infrastructure is necessary to ensure appropriate, effective and efficient investment; to support strategic decision making with regard to national and landmark infrastructure; and to ensure Australia achieves the maximum outcome for the money invested.
- Processes for funding research infrastructure should be transparent, provide effective use of funds and clearly target intended outcomes.

Guiding considerations

- *With finite resources, Australia needs to choose where to target its investments in research infrastructure.*
- *Australia needs to consider its priorities in both a national and an international context.*
- *Transparent processes to determine priorities will lead to better informed and more widely supported outcomes.*
- *The strategic identification of capabilities and priorities should be through a consultative roadmapping process every three years.*

Excellence in research infrastructure

- Proposals for investment in all scales of research infrastructure should be evaluated on the basis of their ability to create excellent infrastructure.
- Governance structures should be robust and fit for purpose to ensure the delivery of excellence in research infrastructure.

Guiding considerations

- *Excellence in research infrastructure is essential to ensuring Australia is able to continue to compete internationally and contributes to a strong innovation system.*

Collaboration

- Funding should favour investments that demonstrate collaborative approaches for the creation and development of research infrastructure and that foster and facilitate a collaborative research culture.

Guiding considerations

- *Collaboration is a key driver of innovation and is critical to ensuring the research community can deliver the outcomes Australia needs.*
- *There are often economic and efficiency benefits from taking a collaborative approach to establishing and operating research infrastructure.*

Co-investment

- Co-investment in research infrastructure is desirable as it demonstrates a commitment by the investing party/ies to the project. Any program requirements for co-investment should be flexible to leverage maximum support.

Guiding considerations

- *Flexibility and transparency in co-investment requirements can lead to greater overall leverage and improves the ability of States and Territories to coordinate support for research infrastructure with the Australian Government.*
- *Opportunities for industry co-investment in research infrastructure facilities should be clear and encouraged as a basis for closer research collaboration.*

Access and Pricing for Australian-based infrastructure

- Research infrastructure at the national and landmark scale should be made widely accessible to publicly funded researchers.
- Research infrastructure at the local scale should be made accessible to the extent possible in order to maximise use and support collaboration between institutions.
- Pricing policies for research infrastructure should be clear and transparent and allow for flexibility in the charging model, while still maximising the public benefit.
- Access to and pricing of finite research infrastructure resources should be based on a combination of factors including merit, co-investment, the role of the host institution, opportunities for early career researchers, and supporting collaborative research.

Guiding considerations

- *An effective access regime ensures that research infrastructure is put to optimum use and fosters collaboration both nationally and internationally.*
- *An effective pricing policy for publicly funded research infrastructure ensures that meritorious research is not priced out of the market.*
- *Clear and transparent pricing policies allow for access costs to be built into research funding proposals.*

Access to overseas-based infrastructure

- Research infrastructure funding programs should consider Australian membership of, or contribution to the construction of, overseas facilities as the development of infrastructure in Australia is not always the most cost effective solution to providing research infrastructure.
- Research funding programs should consider requests for funding Australian researcher access to overseas facilities.
- Where possible Australian research infrastructure facilities should be encouraged to provide access to International researchers to foster international links and collaborations and build local skills.

Guiding considerations

- *Funding access to overseas-based research infrastructure ensures Australian researchers can utilise the best infrastructure available and furthers Australia's engagement with the global research community.*

Evaluation and Monitoring

- Research infrastructure funding programs should incorporate procedures for regular and rigorous monitoring and evaluation to ensure the effective use of public funds.

Guiding considerations

- *Evaluation and monitoring is essential to determine whether the research infrastructure has delivered its desired outcomes and achieved its objectives over the short and medium term, as well as over its whole life-cycle.*
- *Consideration of whether the research infrastructure continues to be a national priority is assisted through rigorous evaluation.*

APPENDIX B

DETAILS OF THE 2011 ROADMAP DEVELOPMENT PROCESS

The development of the *2011 Strategic Roadmap for Australian Research Infrastructure* took place primarily in the first half of 2011. There were three key stages of the document's development in the following order:

- Release of a Discussion Paper for consultation
- Release of an Exposure Draft of the 2011 Roadmap for consultation
- Release of the final *2011 Strategic Roadmap for Australian Research Infrastructure*.

The 2011 Roadmap was developed under the strategic leadership of the National Research Infrastructure Council and the roadmapping process was designed to allow for the widest possible consultation.

A key aspect of the roadmapping process was the use of Expert Working Groups to provide specialist advice to the department on developments in research and priorities for research infrastructure.

Six Expert Working Groups were established using the National Research Priorities (NRPs)[78] as an organising principle, with additional groups for 'Understanding Cultures and Communities' and 'eResearch Infrastructure'.

The formation of the Expert Working Groups around the NRPs with the two additional groups reflects the process taken to create both the 2006 and 2008 Roadmaps.

The six Expert Working Groups in the 2011 process were as follows:

- Environmentally Sustainable Australia
- Promoting and Maintaining Good Health
- Frontier Technologies
- Safeguarding Australia
- Understanding Cultures and Communities
- eResearch Infrastructure

The department sought nominations from a wide range of stakeholders in late 2010 and received more than 400 nominations. Members of these groups were drawn from a wide range of organisations and discipline areas. They were selected on the basis of their skills and knowledge in specific areas, and their ability to engage with and seek views of their peers and other stakeholders. A list of members of the Expert Working Groups is provided on the following pages.

The Expert Working Groups, supported by the department, developed a Discussion Paper for consultation. The purpose of the Discussion Paper was to seek feedback from stakeholders on the research infrastructure requirements to support excellent research and innovation outcomes into the future.

78 www.innovation.gov.au/AboutUs/KeyPublications/Documents/InnovationPortfolioFactSheets.pdf, pg 144

Following analysis of the over 200 submissions and input from stakeholder consultations, an Exposure Draft of the 2011 Roadmap was prepared and released. This involved synthesising the identified research infrastructure needs into a set of priority capability areas of a national scale.

Over 150 submissions were received in response to the Exposure Draft. The submissions were considered, in conjunction with further targeted consultations, during the preparation of the final 2011 Roadmap.

ENVIRONMENTALLY SUSTAINABLE AUSTRALIA

Dr John Gunn (Chief Scientist, Australian Antarctic Division) – Chair

Professor Vassiliios G Agelidis (The University of New South Wales)

Dr Andrew Barnicoat (Geoscience Australia)

Dr John Church (CSIRO)

Dr Colin Creighton (Fisheries Research and Development Corporation and the Grains Research and Development Corporation)

Dr Nick D'Adamo (UNESCO)

Professor David Day (Flinders University)

Professor Stephen Dovers (The Australian National University)

Professor Bronwyn Gillanders (The University of Adelaide)

Mr Warwick McDonald (Bureau of Meteorology)

Dr Phillip McFadden

Dr Neil McKenzie (CSIRO)

Dr Tony Press (Antarctic Climate and Ecosystems Cooperative Research Centre)

Dr Russell Reichelt (Great Barrier Reef Marine Park Authority)

Professor Paul Sanders (Queensland University of Technology)

Professor Mike Sandiford (The University of Melbourne)

Dr Brett Summerell (The Royal Botanic Gardens and Domain Trust)

Professor Grant Wardell-Johnson (Curtin University)

PROMOTING AND MAINTAINING GOOD HEALTH

Professor Mike Calford (Deputy Vice-Chancellor (Research), The University of Newcastle) – Chair

Professor Judith Clements (Queensland University of Technology)

Professor Simon Foote (University of Tasmania)

Professor Doug Hilton (Walter and Eliza Hall Institute of Medical Research)

Dr Paul Jelfs (Australian Bureau of Statistics)

Professor Louisa Jorm (University of Western Sydney)

Professor Paul Keall (The University of Sydney)

Professor Peter Leedman (The University of Western Australia)

Professor Julio Licinio (The Australian National University)

Professor Kerin O'Dea (University of South Australia)

Professor Ian Smith (Monash University)

Dr Ron Weiner (Australian Nuclear Science and Technology Organisation)

FRONTIER TECHNOLOGIES

Dr Calum Drummond (Group Executive, Manufacturing, Materials and Minerals, CSIRO) – Chair

Dr Phil Diamond (CSIRO)

Professor Lorenzo Faraone (The University of Western Australia)

Associate Professor John Fletcher (The University of New South Wales)

Dr Marie-Claude Gregoire (Australian Nuclear Science and Technology Organisation)

Professor Tanya Monro (The University of Adelaide)

Professor Paddy Nixon (University of Tasmania)

Emeritus Professor John O'Callaghan (The Australian National University)

Professor Mary O'Kane (NSW Chief Scientist and Scientific Engineer)

Professor Bernard Pailthorpe (The University of Queensland)

Professor Steven Prawer (The University of Melbourne)

Professor Judy Raper (University of Wollongong)

Professor Robert Williamson (The Australian National University)

SAFEGUARDING AUSTRALIA

Dr Alastair Robertson (Group Executive, Food, Health and Life Science Industries, CSIRO) – Chair

Dr Laurie Besley (National Measurement Institute)

Mr Brett Biddington (Biddington Research Pty Ltd.)

Dr Regina Fogarty (Industry & Investment NSW)

Associate Professor James Gilkerson (The University of Melbourne)

Professor Andrew John Goldsmith (University of Wollongong)

Dr John Percival (Defence Science and Technology Organisation)

Professor Susan Pond (Commercialisation Australia)

Professor John Roddick (Flinders University)

Dr John Stambas (Deakin University)

Professor Richard Tay (La Trobe University)

Professor Sue Thomas (Charles Sturt University)

Associate Professor Colin Wastell (Macquarie University)

Professor Tony Watson (Edith Cowan University)

UNDERSTANDING CULTURES AND COMMUNITIES

Professor Rae Frances (Dean of Arts, Monash University) – Chair

Professor Pal Ahluwalia (University of South Australia)

Ms Margaret Anderson (History SA)

Dr Paul Arthur (The Australian National University)

Professor Alison Bashford (The University of Sydney)

Professor Ann Capling (The University of Melbourne)

Mr Alec Coles (Western Australian Museum)

Distinguished Professor Stephen Crain (Macquarie University)

Dr Rebecca Johnson (Australian Museum)

Dr Marcus Lane (CSIRO)

Ms Anne-Marie Schwirtlich (National Library of Australia)

Dr Luke Taylor (Australian Institute of Aboriginal and Torres Strait Studies)

Dr Nicholas Thieberger (The University of Melbourne)

Professor Mandy Thomas (The Australian National University)

Ms Gemma Van Halderen (Australian Bureau of Statistics)

Professor Andrew Wells (Australian Research Council)

eRESEARCH INFRASTRUCTURE

Professor Attila Brungs (Deputy Vice-Chancellor and Vice-President (Research), University of Technology, Sydney) – Chair

Professor Paul Bonnington (Monash University)

Professor Andrew Cheetham (University of Western Sydney)

Dr Joanne Daly (CSIRO)

Mr Peter Nikoletatos (Curtin University)

Mrs Linda O'Brien (Griffith University)

Professor Andy Pitman (The University of New South Wales)

Mr Antony Stinziani (Geoscience Australia)

Ms Judy Stokker (Queensland University of Technology)

Dr Darrell Williamson (CSIRO)

Dr Judith Winternitz (Department of Broadband, Communications and the Digital Economy)