Australian Government

National Research Infrastructure Roadmap

Draft
2016 National Research Infrastructure Roadmap

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Consultation

The 2016 National Research Infrastructure Roadmap will guide the Australian Government in its national research infrastructure investment decisions over the next ten years.

Released on 5 December 2016, this Draft 2016 National Research Infrastructure Roadmap (Draft 2016 Roadmap) is now available for comment and is the result of the extensive consultations between July and September 2016 following the release of a National Research Infrastructure Capability Issues Paper on 20 July 2016.

Your comment and feedback is sought on this Draft and will be used to finalise the Roadmap to be provided to Government in February 2017.

The draft Roadmap sets out Australia's national research infrastructure focus areas for the coming decade. These priorities will support areas of research, science and innovation in areas where Australia excels, can deliver the greatest long-term national benefit and foster strategic international partnerships.

Stakeholder feedback is being sought on the Draft 2016 Roadmap ahead of a final 2016 Roadmap being provided to Government. The Expert Working Group (EWG) is particularly interested in views on the key recommendations and the research infrastructure focus areas and associated priorities. In framing your response please provide a rationale for your position or perspective and where appropriate, potential alternatives.

If you wish to provide comments on the Draft 2016 Roadmap, you can do so at www.education.gov.au/2016-national-research-infrastructure-roadmap.

Please note we are not looking for specific project submissions or proposals. Responses should be limited to 1000 words.

Comments on the Draft 2016 Roadmap must be received by Monday 16 January 2017.

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Executive Summary

The 2016 National Research Infrastructure Roadmap identifies priority research infrastructure for the coming decade in nine areas that will underpin research in which Australia excels, to deliver long-term national benefit and foster strategic international partnerships.

Outstanding science and research is a critical foundation of an innovative and prosperous modern society. Globally competitive research depends on access to first-class research equipment, systems and services, collectively referred to as research infrastructure.

Australia today is the beneficiary of internationally recognised and highly efficient research infrastructure that consistently delivers outstanding returns. It has been developed through the implementation of a series of strategic roadmaps funded by successive Australian governments, with support from state and territory governments, universities and research agencies.

It is time, now, to build on this foundation of Australian prosperity and reach for excellence in the decade ahead.

There are four layers that make up the Australian research infrastructure system:

1. Institutional research infrastructure
2. National research infrastructure
3. Landmark research infrastructure
4. Global research infrastructure

For the purpose of the 2016 National Research Infrastructure Roadmap (2016 Roadmap), layers two, three and four have been addressed, guided by the following definition:

> ***National research infrastructure comprises the nationally significant assets, facilities and services to support leading-edge research and innovation. It is accessible to publicly and privately funded users across Australia, and internationally.***

Institutional infrastructure, which while critical, rightly falls within the domain of the individual institutions has not been considered.

With this frame in view, Australia's existing national research infrastructure system serves over 35,000 researchers and comprises a highly effective network of facilities and projects under the National Collaborative Research Infrastructure Strategy (NCRIS), Landmark facilities, including the Australian Synchrotron and the OPAL Research Reactor operated by publicly funded research agencies (PFRAs) and large-scale international collaborations such as the Square Kilometre Array (SKA).

Coordinated planning and collaboration across research domains has consistently enabled Australia to achieve scale in emerging areas of research infrastructure and national priority. We have successfully built on our national strengths in areas such as fabrication at the micro and nanoscale, environmental monitoring and modelling, data platforms, the design and development of complex instrumentation, quantum computation and high-throughput chemistry.

Research in all of these fields has the potential to significantly transform the way we live and the patterns of economic opportunity across the world. It is greatly to our benefit that Australia's best researchers are equipped to make a strong contribution through access to leading facilities both domestically and overseas.

In December 2015 the Australian Government reaffirmed its commitment to national research infrastructure through the National Innovation and Science Agenda (NISA). It boosted funding for the existing NCRIS funded facilities and projects, the Australian Synchrotron and the SKA and commissioned the development of the 2016 Roadmap.

As NISA recognised, ongoing investment, supported by a clearly defined strategy, is essential if we are to maintain the quality and scale of our national research infrastructure portfolio. We must monitor performance, plan strategically for obsolescence and replacement, and reorient or increase capacity in areas of greatest opportunity across this complex portfolio.

> Internationally significant research that will underpin innovation, economic growth and societal benefit depends on access to leading edge equipment, systems and services. Addressing these needs at national scale, collaboratively and strategically, is the most efficient way to achieve our goals.

In particular, the importance of the Government's role cannot be overstated. It is not simply the leading architect of the national strategy but the major investor, and the anchor that provides state and territory governments, universities and research agencies with planning security to underpin their co-investment.

This responsibility must be framed within Australia's broader agenda for national growth, alongside key elements such as the National Science and Research Priorities, the Industry Growth Centres, the Medical Research Future Fund (MRFF) and the Biomedical Translation Fund (BTF).

In this context, the Terms of Reference (ToR) for the 2016 Roadmap call for a framework to maximise the benefits of existing national research infrastructure built over the last ten years and identify the next generation of research infrastructure that will optimise our national science and research effort.

The development of specific investment plans falls beyond the scope of the 2016 Roadmap.

The nine priorities put forward in response to the ToR were framed through extensive consultations with key stakeholders including the research community, universities, industry, state and federal government agencies, PFRAs, and operators of research infrastructure facilities.

The Expert Working Group (EWG) will provide separately guidance to the Government on priorities and possible allocation of operating funding under NCRIS.

Key Recommendations

The following are overarching recommendations that focus on existing strengths and identify gaps that when addressed will further optimise our national research infrastructure system.

1. **Adopt Nine Focus Areas** and their priorities to address future needs, fulfil our national interests and build on our existing national capabilities. These focus areas complement the National Science and Research Priorities and the Industry Growth Centres. They are:

- Digital data and eResearch platforms
- Platforms for Humanities, Arts and Social Sciences (HASS)
- Characterisation
- Advanced fabrication and manufacturing
- Astronomy and advanced physics
- Environmental systems
- Biosecurity
- Complex biology
- Therapeutic development

2. **Establish a Research Infrastructure National Advisory Group** to provide independent advice to Government on future planning and investment for a whole of government response to national research infrastructure. It should:
    - advise on priorities for National infrastructure and Global infrastructure
    - make recommendations on Landmark infrastructure
    - review the existing National infrastructure base to enhance, restructure, re-engineer or terminate existing activity and
    - update the ten-year vision of the roadmap every five years.
3. **Develop a Roadmap Investment Plan** that will actively engage with all levels of Federal and State government, universities, industry, philanthropy, research institutions and research agencies. The investment plan must take a portfolio based approach and consider the business case for focus areas including analysis of funding sources for capital and operational needs, access rules, outreach programs and international engagement.
4. **Address the Needs of Complementary Initiatives** such as the newly established Medical Research Future Fund (MRFF) and the Biomedical Translation Fund (BTF). These will increase demand for research infrastructure and must be considered as an integral part of any roadmap investment plan.
5. **Recognise that a Skilled Workforce** is critical to national research infrastructure. Ongoing commitment to training and career progression, not only by the facilities and projects but also by the universities and research institutions that harness them, is essential.
6. **Note that Existing Landmark Facilities** such as the Australian Animal Health Laboratory (AAHL), Australian Synchrotron, the OPAL Nuclear Research Reactor, and the Marine National Facility (RV Investigator) will require ongoing investment.
7. **Implement a Coordinated Approach to International Engagement** to optimise the benefits of international memberships and partnerships, including access to global facilities and participation in strategic collaborations.
8. **Raise Awareness** of national research infrastructure through outreach activities with both national and international collaborators and the end users of research such as industry and business. Future governance arrangements should monitor progress and provide an annual update, including case studies, to promote further engagement.
9. **Urgently Address National High Performance Computing (HPC)** needs coupled with a review of existing governance arrangements to ensure future positioning is strategic and accessible.

National Research Infrastructure Focus Areas

The 2016 Roadmap has identified the following nine focus areas that require ongoing support to ensure that Australia will be able to maintain its position as an emerging or established global leader.

Digital Data and eResearch Platforms – All areas of research are increasingly dependent on data and eResearch infrastructure. Through national, state and institutional investments over the past decade, Australia has built an internationally competitive eResearch system. Consolidating the gains of the past decade through the creation of an Australian Data Cloud will deliver a more integrated, coherent and reliable system to meet the needs of data-intensive, cross-disciplinary and global collaborative research.

Platforms for Humanities, Arts and Social Sciences (HASS) – Bringing together multiple data sets from many social science disciplines will enable the harvest and re-use of data for research purposes. Improved interoperability of existing portals and facilities, and leveraging next generation technologies will deliver a greater degree of integration across state, national and international institutions. This approach will be revolutionary and will include the harmonisation of platforms for Indigenous research.

Characterisation – Technologies in advanced microscopy and microanalysis underpin modern science, medicine, engineering and industrial innovation. Strategic investment in diverse toolsets to explore the structure, chemistry and functionality of natural and synthetic systems will enable blue-sky research and the solution of applied industrial and translational problems. This investment will introduce new and potentially disruptive technologies to strengthen existing capability.

Maintaining and enhancing Australia's characterisation research infrastructure is essential for the competitiveness of Australian research into new materials and biological processes. Visualisation and modelling are important aspects of characterisation infrastructure and will be critical to maximising the development and adoption of new technologies and techniques. A number of national and institutional level facilities already exist, and there is scope for further development to properly leverage this evolving capability.

Advanced Fabrication and Manufacturing – Australia's world leading research in nano-electronics, advanced materials and photonics relies on access to cutting-edge fabrication infrastructure with diverse applications including advanced sensing, communications, quantum computing, energy capture and storage, new medical treatments, diagnostics and disease prevention. Future research infrastructure must deliver capabilities for novel materials development, new and hybrid device fabrication and the integration of devices and systems to create industry-ready prototypes.

Astronomy and Advanced Physics – Australia is renowned for its astronomy research and instrumentation development. For astronomy, the facilities required are global and need to be built where geographic and other considerations allow the best possible performance. A paramount need for Australian optical astronomy today is increased access to international, eight-metre-class telescopes. In radio astronomy, our ongoing participation in the international SKA consortium is building on Australia's position as one of the world's best radio-quiet sites. Participation in international consortia remains necessary to maintain optical and radio astronomy capability.

Australia's advanced physics capability will underpin the development of next generation instrumentation, critical to maintaining our edge in areas such as quantum computation, non-invasive scanning and additive manufacturing. New quantum technologies will provide observational techniques that will lead to the development of technologies such as quantum optics used for gravity wave detection. The capacity to develop bespoke instrumentation – to convert from lab-tests to prototype – is a critical 'next step' for basic research with the potential for future commercial opportunities.

Environmental Systems – Enhancing and integrating observational research infrastructure supporting predictive modelling will strengthen environmental management, risk assessments, primary production, and resource development whilst sustaining biodiversity. Predicting impacts on environmental systems is the necessary first step in the management of our continent and surrounding oceans, in order to adapt to climate change to ensure domestic and global sustainable growth. Australia can build on its unique geographic, economic and intellectual capabilities to become a global leader in the integration of observations, modelling and prediction to maximise innovative economic opportunities.

Biosecurity – A coordinated and enhanced biosecurity capability linking government, industry, researchers and the general community will better manage risks. Protecting the health of our citizens, habitat and primary industries requires continuous innovation. A national approach addressing biosecurity concerns, ideally at the closest geographic point of incursion, will yield better outcomes.

Complex Biology – Global advances in medical, agricultural and environmental research are increasingly enabled by biomolecular research capabilities. While Australia has robust scientific infrastructure across the four technology platforms – genomics, proteomics, metabolomics and bioinformatics – efficiencies of scale and increased opportunities for interdisciplinary research by grouping or networking existing life sciences facilities will ensure Australia continues as a world leader in human, agricultural and environmental genetics.

Therapeutic Development – The translation of novel molecular candidates into ready-for-market therapies is a current and future national priority. However, there are significant gaps in Australia's translation and product development capabilities which limits our capacity to develop new therapies or medical devices. Enabling infrastructure to support translation through to clinical trials is needed to keep future product development in Australia. Linkage of state and federal health and disease control data sets will be necessary to realise the best research outcomes.

Two National Facilities Requiring Urgent Consideration

National High Performance Computing (HPC) – National HPC underpins the most advanced and data-intensive research fields, such as medical science, environmental modelling, physics and astronomy and is vital to maintaining a globally competitive research system. An immediate priority is the need to refresh Australia's national HPC. This should be coupled with a review of existing governance arrangements to maximise the strategic position and accessibility of national HPC.

Australian Animal Health Laboratory (AAHL) – This facility currently supports research in exotic livestock disease and high risk zoonotic diseases. AAHL is equipped to handle infected livestock at the highest physical containment level, known as biosafety level 4 (BSL4). It also houses an insectary where a variety of insect borne diseases affecting humans and animals can be contained and studied. AAHL is a unique national capability that needs to be upgraded to ensure compliance with regulatory requirements. Its role is discussed further under Biosecurity.

1 National Research Infrastructure Framework

1.1 Context

National research infrastructure represents a portfolio of national assets that enable transformational research and innovation to:

- Serve the national interest through critical functions such as weather prediction, disaster preparation and response, cyber security, biosecurity, environmental management and coastal shipping
- Underpin decision-making and long term planning in agriculture, mining, telecommunications, healthcare and other sectors
- Support the growth of industries developing new-to-market products, and
- Bolster the international rankings of our universities thereby securing Australia as a desirable destination for global talent.

In coming years we will see agriculture revolutionised by sensors, crop modification and automation.[1] Healthcare will be streamlined, with increasing numbers of tests being conducted by patients themselves using wearable and in-home personal devices, and treatments will exhibit exquisite therapeutic precision.[2] Robotics will reshape many industries, from manufacturing, logistics and aged care, supported by advances in artificial intelligence, sensors and battery technology.[3] Light vehicle transport will be upended, with a shift to driverless fleet owned vehicles and the substitution of fossil fuel powered vehicles by battery electric vehicles.[4]

Australia must address future environmental challenges to maintain the productivity of our agricultural and resources sectors and meet the needs of our growing population in a time of increased climate variability. For example, weather prediction models can inform us about where and when certain crops have the potential to maximise yields.

Research infrastructure can play a significant role in helping researchers, industry and society meet disruption head on by enabling greater capacity and improving efficiency.

Taking an example beyond our own shores, large data infrastructure such as the European Bioinformatics Institute (EBI) has delivered significant benefit and efficiency to European health research. This benefit is estimated to be worth £1 billion (A$1.7 billion) – equivalent to more than 20 times the direct operational cost of £47 million (A$79 million) per annum of the facility.[5]

The 2014 National Commission of Audit (NCOA) noted that the Government provides around $9 billion per year to support Australian research and innovation and that Australia's research system generally performs well relative to other nations.[6] NCOA noted that since 2001, the Government has provided a series of funding programs for large-scale research infrastructure. This investment has created assets and generated expertise that have positioned the Australian research sector strongly in world terms, both to compete with the best researchers around the world and to participate in global collaborations

[1] Australian Council of Learned Academies (2015), Australia's Agricultural Futures
[2] PricewaterhouseCoopers (2014), Healthcare delivery of the future
[3] Boston Consulting Group (2016), The Robotics Revolution: The Next Great Leap in Manufacturing
[4] Boston Consulting Group (2016), The Autonomous Vehicle: The Car of the Future
[5] http://www.beagrie.com/static/resource/EBI-impact-summary.pdf
[6] http://www.ncoa.gov.au/report/phase-one/part-b/8-2-research-and-development.html

of direct benefit to Australia.[7] NCOA recommended that the Government should commit to "ongoing funding for critical research infrastructure in Australia, informed by a reassessment of existing research infrastructure provision and requirements".

The Productivity Commission has identified two rationales for public support of science and innovation: first, governments need to fund research and development associated with their own core functions such as defence technology and biosecurity concerns and second, because not all of the benefits from research can be captured by the innovator, with some benefits 'spilling over' to later researchers or adopters. These positive spillovers mean that some research that would benefit the overall economy might not be undertaken by business, as each individual business would not receive a sufficient return.[8]

> Investment in large-scale research infrastructure has positioned the Australian research sector strongly in world terms, both to compete with the best researchers around the world and to participate in global collaborations of direct benefit to Australia. (NCOA)

The NCOA recommendation was in part addressed through additional operational funding for NCRIS since 2015. In December 2015, the Government made a significant $2.3 billion investment over ten years in national research infrastructure under NISA. This commitment provided long-term surety to the operations of the existing facilities, and capital expenditure on the SKA. Of particular significance, NISA included a commitment that further investment in national research infrastructure should be guided by regular national roadmaps.

Government Support

Australian Government funding for nationally significant research infrastructure has been varied and significant over the last 15 years. The Government's first major investment from 2001 to 2005 through the $150 million Major National Research Facilities (MNRF) program provided competitive funding for major research facilities with a strong emphasis on co-investment and self-sustainability. The program was not a success, however, with none of the facilities achieving self-sustainability. Approximately half were integrated into NCRIS, while the rest were absorbed by universities or superseded by new investments.

A strategic investment of over $2.8 billion was made between 2005 and 2016 under NCRIS to provide accessible, nationally networked research infrastructure. This investment generated over $1 billion in co-investment from universities and state governments. The initial NCRIS investment of $542 million from 2005 to 2011, was guided by the 2006 national roadmap. Importantly, in this first stage of NCRIS both capital and operating funding was provided. From 1 July 2013 only operational funding was available. The NISA announcement in December 2015 included the Government commitment to ongoing operational funding, bringing certainty to the NCRIS program. Capital funding remains unresolved.

[7] http://www.ncoa.gov.au/report/appendix-vol-2/10-2-research-and-development.html
[8] http://www.pc.gov.au/inquiries/completed/science/report

From 2009 to 2012 the Super Science Initiative (SSI)[9] expanded the NCRIS network and funded research facilities such as ANSTO and AIMS and new landmark infrastructure such as the RV Investigator. The absence of operational funding under SSI was a significant drawback with long-term implications.

At the same time, there has been ongoing investment through direct funding of PFRAs such as the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Australian Nuclear Science and Technology Organisation (ANSTO), Geoscience Australia (GA), the Bureau of Meteorology (BOM), the Australian Antarctic Division (AAD) and the Australian Institute of Marine Science (AIMS). These organisations operate national research infrastructure where the facility meets the mission and strategic intent of the organisation.

The Government also provides support for research infrastructure through the ARC Linkage Infrastructure Equipment and Facilities (LIEF) grants scheme.

Government Leadership

To encourage investment in national research infrastructure, the Government has consistently taken a leadership role providing state governments, universities and PFRAs with planning security to underpin their co-investment. The importance of the Government's role in protecting the national research infrastructure investment cannot be overstated.

Research infrastructure at both the national and institutional level underpins the research outcomes that have led to substantial improvements in the position of Australian universities in international rankings. Universities' investment in their own institutional research infrastructure and their access to national research infrastructure has enabled them to do the research that supports a virtuous cycle that increases the prestige of the universities, thereby enabling them to continue to attract the best students and world leading researchers.

> Clustering of research and industry activities is greatly enhanced when research infrastructure is also available.

In economic terms, investment in national-scale research infrastructure in Australia or internationally is the government response to market failure as there is no functioning market to address the gap. The Government's intervention in research infrastructure corrects this failure, supporting a vision that research infrastructure contributes to economic productivity and improved social outcomes. The 2014 KPMG report on NCRIS noted the existence of market failure and the resultant need for Government intervention and that NCRIS has made a substantial contribution towards scientific research capability as well as research outcomes in Australia.[10]

[9] The SSI funded through EIF, separately contributed over $2.3 billion from 2009 to 2015 for the construction and development of teaching and research infrastructure, predominantly in the university sector. The HEEF established in 2008 as a $6 billion perpetual fund, was rolled into the EIF in 2009. The EIF was constrained by the policy parameters of the other Funds (health and economic infrastructure) as funding legislation would not allow funding of operating expenses, in line with funding for economic infrastructure. EIF closed in 2014 and its balance of $3.7 billion was allocated to the ARF which has subsequently been closed.

[10] KPMG (2014), National Collaborative Research Infrastructure Strategy Project Reviews, Overarching Report

Industry Engagement

There is strong evidence of industry engagement across national research infrastructure, and it is important to continue to ensure it is a priority. Clustering of research and industry activities is greatly enhanced when research infrastructure is also available.

In recent years the Melbourne Biomedical Precinct has attracted over $5 billion of private and public investments for the construction of state-of-the art hospitals, research buildings and infrastructure. The precinct has attracted the Victorian Comprehensive Cancer Centre Project, the Melbourne Brain Centre, the Peter Doherty Institute for Infection and Immunity and the Bio21 Institute.

The Bio21 Institute is one of Australia's largest biotechnology research institutes and includes sophisticated analytical national research infrastructure platforms funded through NCRIS. It is accessed by more than 500 researchers across the chemical, biomedical and bioengineering sciences. For nearly a decade CSL, Australia's largest multinational biopharmaceutical company, has been a partner in the Bio21 Institute. Through this successful partnership CSL is investing in a $36.4 million expansion of the Bio21 Institute. This will include the CSL Global Hub for Research and Translational Medicine, housing 150 CSL research scientists.

This type of clustering is critical for advancing medical research and developing new treatments. The new facilities are changing the ability of scientists to conduct complementary research, expanding new research possibilities and accelerating research outcomes.

Future investment in national research infrastructure must include the requirement to foster strong links with industry and business. Facilities and projects funded under the NCRIS network are required to have industry engagement plans and industry engagement is a mission requirement for PFRAs. These industry engagement plans and outcomes should be published on an annual basis.

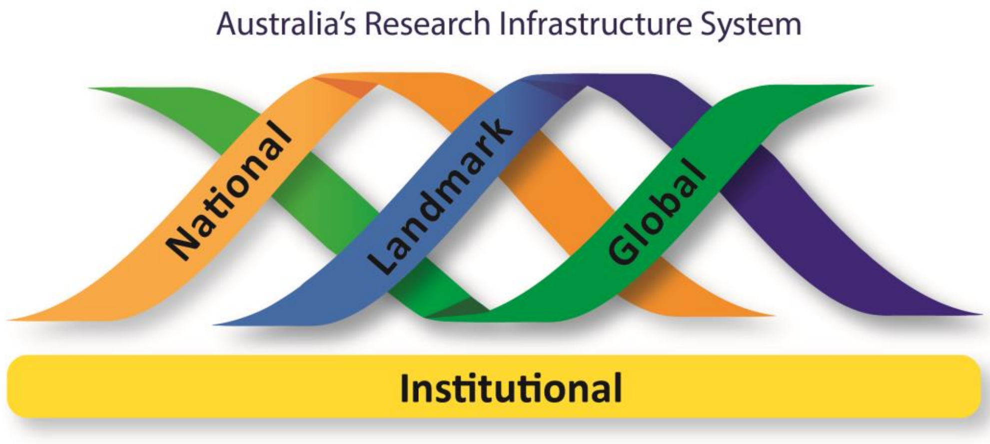
1.2 National Approach for Research Infrastructure

For the purpose of the 2016 Roadmap, we use the following definition:

Definition of National Research Infrastructure

National research infrastructure comprises the nationally significant assets, facilities and services to support leading-edge research and innovation. It is accessible to publicly and privately funded users across Australia, and internationally.

Figure 1: Australia's Research Infrastructure System



There are four layers that make up Australia's research infrastructure system:

1) **Institutional Research Infrastructure** – this foundation layer rests with institutions and is not in scope for the 2016 Roadmap. It is acknowledged to be an important precursor to the development of national research infrastructure. The three layers that follow are the focus of the 2016 Roadmap.
2) **National Research Infrastructure** – optimises the use of scarce resources to create scale from geographically distributed and highly networked facilities. This drives efficiency by reducing duplication of facilities, equipment and skills across institutions by focusing on national research infrastructure that is highly collaborative, cross disciplinary, supported by the best highly skilled technical workforce and representing national best practice.
3) **Landmark Research Infrastructure** – acknowledges that there is a category of research infrastructure that is of such scale that the national interest is best served by landmark facilities such as the OPAL reactor operated by ANSTO, and AAHL operated by CSIRO. The decision to invest in landmark infrastructure is made from time to time by Government.
4) **Global Research Infrastructure** – is multinational, collaborative and of a scale where the cost of establishment is beyond the resources or expertise of a single nation. Access to international facilities is vitally important in the Australian context as it fosters collaboration and provides access to infrastructure that might not otherwise be available.

A successful national infrastructure system must be well understood, cohesive and strategic so as to maximise available resources.

Planning for Investment

Australia has used research infrastructure roadmaps to identify and prioritise investments in national research infrastructure since 2006. Roadmaps are a well-established method for prioritising research infrastructure, both at a national and international scale. The European Strategy Forum on Research Infrastructures (ESFRI)[11] Roadmap identifies research infrastructure that will be of benefit to all of Europe. In addition, most European Union (EU) member countries also have their own national roadmaps, as do many non-EU countries.

Australia has produced three research infrastructure roadmaps, in 2006, 2008 and 2011, with NCRIS being the main area of focus. The 2016 Roadmap is the first roadmap to explicitly consider the three layers of national, landmark and global research infrastructure. The broadening of scope recognises the increased integration and interconnectivity of the national research infrastructure system.

While Australian research covers a wide range of domains, not all require national research infrastructure. Research areas not identified through the 2016 Roadmap may be equally important but their infrastructure requirements can be met through institutional or commercially available infrastructure.

1.3 Evolving Strategic Governance

There are two levels of governance that are important to an effective and efficient national research infrastructure system – overarching national governance and program-specific governance.

[11] http://www.esfri.eu/

National Governance

The consultations for the development of the 2016 Roadmap have stressed the importance of long term governance to guide decision making for national research infrastructure. The consensus view is that a successful national infrastructure system must be well understood, cohesive and strategic so as to maximise available resources. This is currently a gap which must be addressed.

Recent reviews have identified that Australia would benefit from a disciplined and better coordinated approach to national research infrastructure and noted that there is no single body providing strategic direction.

The 2016 Roadmap provides an opportunity to consider the need for ongoing independent advice to Government on future planning and investment for a whole of government response to national research infrastructure. This could be achieved through the establishment of a body, made up of independent experts who are highly regarded across the stakeholder community in both the private and public sectors, with responsibility for providing expert advice to the Government.

The governance framework should take a principles-based approach to guide support for national research infrastructure.

National Research Infrastructure Principles

The following principles should inform decisions on future national research infrastructure investment.

- Australia's investment in national research infrastructure should maximise the capability of the research and innovation system to improve productivity, foster economic development and serve the national interest.
- National infrastructure resources should be focused in areas where Australia is, or has the potential to be, world-class in research and provide international leadership.
- Investment in national research infrastructure should be aligned with key Government priorities and initiatives such as the NSRPs, MRFF, BTF and Industry Growth Centres.
- Major infrastructure should be developed on a collaborative, national, non-exclusive basis. Infrastructure funded under the 2016 Roadmap, and in particular NCRIS funded facilities and projects, should serve the research and innovation system broadly, not just the host or funded institutions.
- Australian Government funding should encourage collaboration and co-investment among universities, state and territory governments, PFRAs, independent and private sector research organisations, industry and philanthropy.
- During the development of the business case for each new project, opportunities for industry, philanthropic and international support should be explored.
- The business case should address user-related operational procedures such as the user access plan and outreach.
- Access guidelines should ensure that there are as few barriers as possible to accessing major infrastructure for those undertaking meritorious research.
- Due regard should be given to the whole-of-life costs of major infrastructure, with funding available for operational costs where appropriate.
- The implementation of the 2016 Roadmap should enhance the participation of Australian researchers in the international research system.

A Framework for National Research Infrastructure Governance

The governance framework for national research infrastructure should include the following elements.

- Independent advice to Government on national research infrastructure prioritisation and investment.
- A transparent process for the consideration and prioritisation of national research infrastructure on a national portfolio basis including reinvestment, termination and new proposals.
- A principles-based approach to maintaining, terminating or creating new national research infrastructure based on merit-based access for research excellence, state of the art instruments and methods, innovation, collaboration, national interest, socio-economic impact and international engagement.
- Evaluation of the research and scientific value of existing or new facilities and projects to the national research effort and the national interest.
- Engagement of international experts and peer reviewers in the evaluation process.
- A life cycle approach to the prioritisation of national research infrastructure with a strong focus on emerging opportunities that will optimise the available resources.
- Monitoring and analysis of the international research infrastructure system and emerging trends to identify opportunities for engagement and participation.
- Monitoring of national research infrastructure capability areas, facilities and projects and periodic reviews.
- Regular engagement with the key stakeholders in the national research infrastructure system, the research community and industry both nationally and internationally.
- Transparent communication of the impact and performance of the national research infrastructure system including providing an annual report to Government.
- Regular development of national research infrastructure roadmaps and investment plans.

Program Governance

National research infrastructure facilities and projects must have best-practice governance and management. This includes setting strategy, monitoring performance, managing risk and meeting the expectations of its key stakeholders by remaining relevant and viable.

Currently there are a number of governance arrangements across the NCRIS network that span not for profit companies, unincorporated consortia, representative boards and management boards. Publicly funded research agencies are required to address governance arrangements based on their enabling legislations.

The 2014 independent review by KPMG of NCRIS observed that most facilities and projects had implemented effective governance arrangements that had been designed to meet the needs of the facility or project. Those assessed as particularly effective had a skills based board with an active network that could be drawn upon to support the facility or project, as well as clearly defined roles and responsibilities. In addition, the skills and capability of the facility or project director were considered to have made a significant impact, with those who have both a deep technical and scientific understanding as well as broader commercial acumen performing most impressively.[12]

It is recommended that the governance arrangements for national research infrastructure facilities and projects should include the following characteristics: a skills based board; an active experts network to support the facility or project; and clearly defined roles and responsibilities for the board

[12] KPMG (2014), National Collaborative Research Infrastructure Strategy Project Reviews, Overarching Report

and the management team. In addition, the facility or project director must have the appropriate skill set and capability including a deep technical and scientific understanding and if appropriate, broader commercial acumen.

1.4 Skills and Career Development

Human capital is fundamental to research and the wider innovation system. Skilled technical and management staff are essential to maintaining the highest-quality, most advanced research infrastructure capabilities. The Australian Council of Learned Academies (ACOLA) recently confirmed this in the 2016 Review of Australia's Research Training System.[13] People form the core of the national research infrastructure system – their expertise, skills and passion enable the effective establishment and optimised use and benefit of the facilities. This is particularly the case when supporting industry access and research translation.

As the complexity of the research methods and technologies to undertake ground breaking research grows, advanced mathematics continues to be an important and scarce resource. Maximising the development of algorithms and predictive modelling scenarios, integral to many areas of research, can only be realised with strong mathematical capabilities.

There are two elements to successfully utilising world leading infrastructure. The first element is training and development of both the facility managers and technical staff. Contemporary facilities require managers with deep technical and scientific understanding as well as broader commercial skills. Maintaining and optimising the operation of facilities requires highly qualified specialists to assist researchers with designing their work and to support collaborations between industry and researchers. Career progression is often limited in these specialist areas where the traditional academic pathways are not available, as these roles require researchers to move away from the activities that generally form part of academic advancement. The attraction and retention of quality facility staff can be challenging and there may be skills shortages (in what is an international skills market) where the reward of highly sought after specialists is governed by rigid, academic human resource systems.

The second element is the skill level of researchers. The 2016 ACOLA review made recommendations for improving and enhancing researcher training. In addition to broad research skills there are particular deficits notably but not limited to data analysis and software development to manipulate the ever increasing datasets. While national research infrastructure facilities can provide an enabling and facilitation role, there are limits to the extent that the skills gaps can be addressed by facilities.

Acknowledging that these are significant issues, some national research infrastructure workforce matters are being creatively advanced on a case by case basis. There are a range of measures that might assist including:

- innovative approaches to career progression and skills recognition in academia,
- closer engagement between academia and industry, including secondments and scholarships, including for PhD students, and
- ensuring research infrastructure programs include operational funding for skilled personnel.

[13] http://acola.org.au/PDF/SAF13/SAF13percent20RTSpercent20report.pdf

Case Study - Australian National Fabrication Facility (ANFF) Technology Ambassador Fellows Program

The increasingly diverse user base of the ANFF requires comprehensive and flexible training to support researcher needs. The ANFF Technology Ambassador Fellows program meets this need by embedding leading researchers in the ANFF headquarters, the Melbourne Centre for Nanofabrication, as contributors and consultants for users, staff and industry. The Technology Fellows program proactively builds strong user communities around highly specialised instruments allowing the latest innovations in nanofabrication to be swiftly disseminated across the ANFF network.

Case Study - EMBL Australia Partnership PhD Program

EMBL Australia was created to maximise the benefits of Australia's membership of the European Molecular Biology Laboratory. The EMBL Australia Partnership PhD program allows students in Australia to leverage the expertise, world-class infrastructure and unique multidisciplinary nature of EMBL Australia and the European based EMBL facilities.

1.5 International Engagement

International engagement is a critical element of the national research infrastructure landscape. Australian researchers need access to domestic and international world-class research infrastructure necessary to drive internationally significant and leading research results. While international collaboration can provide access to facilities beyond our means, there must be demonstrated domestic capability for us to participate and in some cases take a leadership role.

For example, Australia’s investment in remote sensing for environmental and oceanic monitoring in facilities such as the Integrated Marine Observing System (IMOS), while small by international standards, has allowed us to participate in international sensing networks resulting in access to data and expertise that has significantly amplified our initial investment. Our ability to continue to participate in international collaborations will be limited without a clear commitment to maintain a standard of research infrastructure commensurate with that of our international partners.

The primary drivers for Australia to participate in global research infrastructure projects are:

- cost effectiveness, as many projects are beyond our financial capability, such as optical astronomy and advanced physics
- large scale collaborations particularly in the areas where data is a significant enabler such as environment and health
- strategic engagement in areas where we have a developed special expertise, such as astronomy and space instrumentation
- alignment with the national interest, and
- leadership and direction setting by having a seat at the table, particularly in new or emerging areas.

Australia has a strong history as a partner or leader in international activities. Already many domestic research infrastructure facilities and projects are involved in international collaborations, either multi-laterally or bi-laterally. These partnerships occur at various levels, ranging from institutional through to government to government.

Case Study - International Ocean Discovery Program (IODP)

The IODP is a large international collaborative research program that undertakes shallow and deep sea drilling to gain a greater understanding the organisms and materials that exist in the oceans, deep seas, sea floor and in the layers below the sea floor around the globe. The drilling technology and borehole instrumentation generates new data on the nature and distribution of life forms, geological activity and resources in the layers below the sea floor. There are plans for future IODP expeditions to explore sub-sea floor life in the Australian marine estate that has rarely been undertaken in the past. Benefits of Australia's membership to the IODP include international collaboration and scientific understanding in areas such as climate and ocean change, biodiversity, deep Earth connections and potential hazards.

The Australian Antarctic Program is an example of global collaboration where national research infrastructure is shared with other parties to the Antarctic Treaty, particularly the United States of America, China, France and Norway. Vessels and infrastructure, both research and logistic, are used collaboratively for operational support and long term projects in Antarctica. Australia helped facilitate China's first visit to east Antarctica 30 years ago, and we have continued to work closely, providing support for each other's Antarctic programs. Australia's influence in the Antarctic Treaty System and the increasing international use of Tasmania's marine and Antarctic research capability and infrastructure as an East Antarctic gateway are evidence of Australia's leadership in this area.

There is currently no mechanism for a co-ordinated national approach to international engagement that seeks out opportunities for collaboration of direct benefit to the national interest. There would be great benefit in establishing such a mechanism to consider international partnerships, access to global facilities and participation in strategic collaborations.

Australia is engaged in a broad range of existing global research infrastructure initiatives, including:

- Square Kilometre Array (SKA)
- European Molecular Biology Laboratory (EMBL)
- Global Ocean Observing System (GOOS)
- Giant Magellan Telescope (GMT)
- International Ocean Discovery Program (IODP)
- International Mouse Phenotyping Consortium
- Global Bioimaging (GBI)
- ITER Fusion Reactor, and
- Research Data Alliance (RDA).

For example, to leverage Australia's imaging capabilities and access the highest-quality and most advanced characterisation capability, Australia must be networked internationally to access major international projects. Both the Australian Microscopy and Microanalysis Research Facility and National Imaging Facility are founding partners in GBI, an international network of collaborating infrastructures that provides biological and biomedical imaging for life scientists. This international network is supported by the EU Horizon 2020 program. Further, our associate membership of the EMBL provides access to European synchrotrons along with image analysis and data processing. In the future this collaboration will provide access to the European X-ray Free Electron Laser when it comes on line in 2017.

Case Study - Giant Magellan Telescope (GMT)

When commissioned in 2022, the Giant Magellan Telescope in Chile will be one of the next class of global scale telescopes that promise to revolutionise our view and understanding of the universe. It will have over six times the collecting area of the largest optical telescope currently in existence. As Australia is a founding member of the GMT international consortium, Australian researchers will have access to this significant world-class facility. Australia's investment at the initial stages as a partner has generated significant benefits two ways. First, through access to enable our astronomical science. Second, through workforce skills sharpened by our contribution of advanced and precision instrumentation under development by Australian researchers and industry.

International accelerator programs and networks that operate multi-billion dollar facilities, such as the European Organization for Nuclear Research (known as CERN), are beyond Australia's resources. Access to these facilities offers unique research and innovation opportunities essential for Australia's research effort and potential industry participation.

Case Study - European Bioinformatics Institute (EBI)

The EBI significantly enhances our domestic capability through access to life science data and services. EBI collects, organises and makes available databases for biomolecular science along with tools to search, download and analyse their content. These databases include DNA and protein sequences and structures, genome annotation, gene expression information, molecular interactions and pathways. EBI is part of a larger global data-sharing agreement involving the USA and Japan. The facilities are located at the Wellcome Genome Campus in Hinxton, Cambridge, UK, one of the world's largest concentrations of scientific and technical capability in genomics. Australia has access to EBI through its associate membership of the EMBL.

1.6 Access to Research Infrastructure

Principles Based Access to National Research Infrastructure

Access is a clear and defining characteristic of national research infrastructure. Access can be constrained by a number of factors including geographical barriers, technical skill and cost. This skews the user base of some facilities to those with the greatest resources or least barriers to access, which can reduce the efficiency, effectiveness and impact of the Government's investment.

Existing national research infrastructure provided by both NCRIS and the PFRAs have access policies in place. These vary according to the facility however the concept of access for meritorious research is common.

The 2016 Roadmap user-access principle is that all researchers across academia and industry should be able to access national research infrastructure, including Landmark facilities, equitably with priority provided to meritorious research. Where factors inhibit equitable access, it is the responsibility of the facility to determine ways to reduce these inhibiting factors to the extent that is practical.

Facilities need to clearly communicate the extent to which general access is or is not available due to other arrangements in place, such as purchased time by industry partners.

Access Principles

Access to national research infrastructure falls into three broad categories, which present different opportunities and challenges for national research infrastructure operators.

- ***Merit*** –access focuses on the merit of the research to be undertaken as the primary determinant for access. In cases of co-investment, at least the Government's funding proportion of the facility should be allocated to merit-based access.
- ***National interest*** –access provides preferential access for activities of national interest that may include reasons of national security or sovereignty.
- ***Commercial*** – access provides the opportunity for industry to use national research infrastructure for commercial benefit, without a review of the scientific merit or requirements to publish the results. Commercial rates are applied.

Each national research infrastructure will make decisions concerning access that are most relevant to the particular dynamics of the user base and services provided. Digital research infrastructure, for example, may treat all users equally, while oversubscribed national infrastructure may use very rigorous merit criteria and access allocations to efficiently utilise resources.

International Access

Access to international research infrastructure has unique challenges. These challenges can include the cost of international travel, national access regimes and the need to balance national interest against the interests of specific research groups. This introduces a greater level of complexity in international collaborations that needs to be addressed.

2 Key National Research Infrastructure

The draft 2016 Roadmap has been developed through extensive consultation starting with the National Research Infrastructure Capability Issues Paper[14], followed by national consultations and facility visits. The EWG has actively engaged with the research community and other key stakeholders so that the future research trends and the research infrastructure identified in the draft 2016 Roadmap reflects their views. In line with the Terms of Reference for the development of the 2016 Roadmap, expert advice was sought on research infrastructure and investment needs.

The Capability Issues Paper identified infrastructure focus areas that underpin the National Science and Research Priorities (NSRPs) and support the needs of the research community. From the resulting 325 submissions and feedback from face to face consultations, nine key focus areas have been identified and explored.

The 2016 Roadmap's research infrastructure focus areas are:

- Digital Data and eResearch Platforms
- Platforms for Humanities, Arts and Social Sciences
- Characterisation
- Advanced Fabrication and Manufacturing
- Astronomy and Advanced Physics
- Environmental Systems
- Biosecurity
- Complex Biology
- Therapeutic Development

The alignment of the research infrastructure focus areas to the NSRPs is shown in Table 1. Many of the research infrastructure focus areas are cross cutting and support the needs of several NSRPs.

In the following sections, the needs of the nine research infrastructure focus areas are considered in light of analysis of our current capabilities and future trends.

Each infrastructure focus area includes a table outlining the priority areas for national research infrastructure and a proposed response. For consistency, responses fall into four groupings outlined in the following table. Context for the groupings and the implementation pathways are outlined in Chapter 3 Implementing the 2016 Roadmap.

Table 1: Four Groupings of National Research Infrastructure (NRI) Responses

NRI responses	Context and approach to response
Explore establishing …	New greenfield investment should be explored as Australia does not have existing or may have limited research infrastructure that can be enhanced.
Explore integration …	Institutional or national research infrastructure already exists and greater integration or new elements should be considered.
Maintain priority for …	Identifies that existing national research infrastructure meets the future need in its current form with no major changes.
Enhance capability in …	Identifies existing national research infrastructure that requires additional investment.

[14] https://docs.education.gov.au/node/41051

While outside the scope of the 2016 Roadmap, the regulatory environment and standards and accreditation were raised as issues during the consultation process.

Regulatory Environment – Fast tracking of clinical trials, medical device development and access to government data were identified as being hampered by the regulatory environment. The EWG acknowledges the Government's recent acceptance of most of the recommendations of the Expert Review of Medicines and Medical Devices Regulation, but ongoing review of this environment, particularly in the bio and nano domains, will ensure that it remains appropriate for emerging translational research opportunities.

Standards and Accreditation – Formal accreditation and certification for facilities and services is critical to fostering greater engagement with industry and other end users of research. International Standards Organisation (ISO) certification and accreditation recognises the standard provided by the research infrastructure facility and demonstrates that the products or service meets specific standards. For some industries, such as health and medical research and development, certification is a legal or contractual requirement.

National research infrastructure facilities need to be encouraged to undertake accreditation or certification. This should be included as part of the planning and identified in annual business plans.

Table 2: Alignment of National Science and Research Priorities and Focus Areas

National Research Infrastructure Focus Areas	National Science and Research Priorities								
	Food	Soil and Water	Transport	Cyber Security	Energy	Resources	Advanced Manufacturing	Environmental Change	Health
Digital Data and eResearch Platforms	Y	Y	Y	Y	Y	Y	Y	Y	Y
Platforms for Humanities, Arts and Social Sciences			Y				Y	Y	Y
Characterisation	Y	Y				Y	Y	Y	Y
Advanced Fabrication and Manufacturing					Y	Y	Y		Y
Astronomy and Advanced Physics				Y	Y		Y	Y	Y
Environmental Systems	Y	Y			Y	Y	Y	Y	
Biosecurity	Y	Y						Y	Y
Complex Biology	Y	Y						Y	Y
Therapeutic Development							Y	Y	Y

2.1 Digital Data and eResearch Platforms

This national eResearch infrastructure area is a cross-cutting capability that serves research collaboration, modelling, data and data analysis needs. It comprises advanced networks; identity, access and authentication services; high performance and cloud computing resources; management of and access to research data; the development and adoption of new digital research techniques; and the integration of all those elements to create digital environments researchers use every day. Research increasingly depends on digital evidence and related data and on digital methods as a new means to progress ideas and advance knowledge. As such, the ability to support those activities through more effective Digital Data and eResearch Platforms becomes critical.

Future Directions

Digital data and eResearch infrastructure enable new research methods, more powerful instruments, accelerate research and open entirely new fields of research.

The significance of high quality digital infrastructure in supporting research is well recognised. Governments across the world are investing billions of dollars in the underpinning eResearch infrastructure necessary to support excellent research. The development of policies that guide the effective use of research data is also an increasing area of international focus.[15,16]

In terms of established infrastructure, the demand for computation and connectivity will continue unabated. A prominent trend is the rising dependence on digital data at new scales, and the complexity and diversity of data being generated. This unprecedented growth in data volume and complexity places increased demand on infrastructure and the skilled staff needed to support it. In addition, the growing importance of software and the development of new algorithmic techniques will continue to open entirely new avenues for research over the next ten years.

To support research in an evolving digital environment Australia must build on previous investments as demand continues to grow. eResearch infrastructure must take advantage of new and emerging technologies and digital methods and support the seamless retention, use and re-use of research relevant data. Australia must stay at the forefront of international developments and should continue to engage with initiatives such as the European Open Science Cloud and internationally recognised guiding principles such as FAIR, which aims to ensure data is findable, accessible, interoperable and reusable[17] over significant periods of time.

What we have

As a result of government and institutional investments over the past decade, Australia has a world leading eResearch infrastructure system that should be enhanced to maintain its current competitive edge in fields as diverse as developmental biology, satellite imagery processing for bushfire understanding and prevention, solar cell efficiency enhancement, more accurate weather forecasting, chemistry for advanced manufacturing and the search for neutron stars. These multi-

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[15] *European Cloud Initiative to give Europe a global lead in the data-driven economy*, April 2016*:* http://europa.eu/rapid/press-release_IP-16-1408_en.htm

[16] *Australian Government Public Data Policy Statement*, December 2015

[17] FAIR Data Guiding Principles were originally developed at a Lorentz Workshop in Leiden, The Netherlands, in January 2014. The Principles have since been formally published in the *Nature* journal *Scientific Data 3*, 2016, and are endorsed by H2020 Programme in *Guidelines on FAIR Data Management in Horizon 2020*, July 2016

level investments have delivered high performance computing (HPC), networks, access and authentication services, better management of and access to research data, national research data storage infrastructure and virtual environments that enable research collaboration.

Much domain specific data-intensive infrastructure also exists. This includes infrastructure such as telescopes and environmental monitoring systems that collect data, projects that collate and aggregate data such as the Australian Urban Research Infrastructure Network (AURIN), the Atlas of Living Australia (ALA) or Population Health Research Network (PHRN), and infrastructure that does both such as IMOS. These domain specific facilities and projects support specific areas of research, and are discussed in more detail under the relevant focus area.

High Performance Computing

HPC makes internationally competitive, computationally intense research possible in Australia. Scale in HPC drives the simulations that are critical to research in many disciplines, improves the speed of discovery, and unlocks the value that exists in our continuously growing research data holdings.

Australia currently has two Tier 1 HPC[18] research facilities – National Computational Infrastructure (NCI) and the Pawsey Supercomputing Centre (Pawsey). While they have provided Australian researchers with substantial national capability up to this point, the facilities and their users have indicated that significant upgrades are required to meet future computation and data needs. Each facility has supporting physical infrastructure and expert staff that will need to be simultaneously maintained and developed.

Both HPC facilities are on the TOP500 list, which ranks the top 500 most powerful computers in the world, but their positions are slipping. The international ranking awarded through the TOP500 is a proxy for the value, or capability, available to researchers. It gives considerable insight into other international investments in advanced computing by governments, academia and industry.

Advanced Research Network

The Australian Research and Education Network (AREN)[19] is a critical part of the eResearch system. It provides high-speed, low latency, high-quality broadband infrastructure between instruments, facilities, campuses and institutions, and globally through the National Research and Education Network (NREN). This dedicated research and education network is essential for connecting Australian researchers with data-intensive resources such as telescopes, storage and computational facilities and the global research community.

Access and Authentication Services

The Australian Access Federation (AAF), Australia's robust access broker, facilitates trusted electronic communication and collaboration between education and research institutions both nationally and internationally. It provides infrastructure and services to validate a researcher's identity in order to access data, either from within their own institution or from another AAF member institution. It provides a crucial part of the national research infrastructure system and enables global collaboration.

[18] Tier 1 is defined as a large-scale national facility (where Tier 0 supports an entire region, e.g. PRACE in Europe, and Tier 2 primarily supports specific institutions or disciplines, e.g. MASSIVE at Monash University).
[19] The AREN is operated by AARNet Pty Ltd

Better Managed Research Data

The Australian National Data Service (ANDS) has been a foundational investment that provides strong support for researchers and institutions to manage and connect their data, both nationally and internationally, and make it FAIR, aligning it to and in many cases leading, international policies and practices.

National Research Data Storage Infrastructure

Australia now has cost-effective, scaled up, shared research data storage services provided through Research Data Services (RDS) that are aimed at improving research collaboration through the storage and provision of access to research data collections of national significance. RDS complements institutional investments by providing infrastructure for the ever growing volume of new and complex data.

Research Cloud Populated with Digital Tools and Virtual Laboratories

Australia's national cloud computing infrastructure and virtual laboratories, provided through National eResearch Collaboration Tools and Resources (NeCTAR) infrastructure, deliver computing and software infrastructure that allows Australia's research community to share computational models, software tools and data. Its domain-oriented virtual environments allow researchers to share research data, models, analysis and workflows. It also supports collaborations across institutional and discipline boundaries to address complex research problems.

What we need

Nationally coordinated eResearch infrastructure that builds on existing capabilities and leverages institutional investments will strengthen Australia's position in the global research environment and ensure that Australian research can accelerate innovation and foster engagement between Australian researchers, international researchers and industry.

The eResearch system cuts across all fields of research. The ability to perform complex computations rapidly, coupled with data storage, complex analytics and data mobility, is essential if Australia is to effectively provide and efficiently take advantage of an evolving data-intensive research environment.

To be a leader in data and eResearch platforms requires the attraction and development of internationally competitive talent and effective training of the next generation of experts in computer science, data sciences, and scientific computing. These experts include the designers of future eResearch architectures, systems software, algorithms, and computational tools. The training commitment will also upskill the research workforce generally to more easily access and use eResearch infrastructure.

High Performance Computing (HPC)

Today's HPC environment has evolved to encompass the needs of big data (processing, analysis, data mining, machine learning), in addition to its traditional role of computational modelling and simulation. The contemporary environment comprises tightly-integrated, high-performance infrastructure able to handle the computational and data-intensive workflows of today's research, together with expertise in computational science, data science and data management.

Australia requires peak national HPC capability to meet the needs of researchers and for international collaborations, such as the SKA and Earth system science. Australia's Tier 1 facilities need upgrading at regular intervals to keep pace with research needs. These upgrades should be coordinated so Australia always has at least one facility operating at full capacity.

To maintain a nationally coordinated Tier 1 HPC capability, national governance arrangements must be addressed. This should increase integration, enhance collaboration and share best practice and expertise.

The 2016 Roadmap has not considered Tier 2 HPC, as services can be affordably purchased by institutions from commercial providers. There may be value in considering the benefits of nationally integrated Tier 2 computing infrastructure in the future, to enhance the value of both national and institutional investments through better alignment.

Case Study - The importance of HPC in Australia

All weather prediction models are dependent on HPC to undertake probabilistic forecasting, which predicts the likelihood of an event occurring by running the same model many times with small variations. Probabilistic models can predict there will be a 70 per cent chance of rain on a Thursday based on many simulations, rather than predict that it will rain on Thursday based on one simulation, which may or may not be accurate and does not provide a confidence level in the prediction.

Farmers need both seasonal and decadal probabilistic weather predictions to maximise yields, reduce inputs (water, nutrients, energy) and manage risks. To improve the probability of a seasonal forecast, or decadal forecasts HPC at a 30 km resolution or less is essential. However, currently no national HPC has the capability to run global decadal models to resolve the synoptic systems at this scale across Australia.

An increase of 10 to 50 times of the current HPC capability would enable global systems at a 30 km resolution to be modelled. This would make a profound improvement to the predictability of weather that is dependent on synoptic scales such as drought, heat waves, cyclones, and low pressure systems. To predict any extreme synoptic events, a minimum of 30 km or less resolution across Australia over decades is essential. This resolution is also critical to continue to collaborate with Japan, the USA or Europe to understand and predict long range weather and climate in Australia.

Advanced Research Network

The AREN should be enhanced and expanded to reach as many researchers as possible. This must be done in a way that achieves the greatest strategic impact for research collaboration.

Priorities include the expansion of the bandwidth to North America and into Asia, full domestic backbone provision at steadily increasing bandwidth to all capital cities and enhanced regional reach at ever higher capacities. This will support data movement between the locations of very large sources of data both here and overseas and the researchers that use that data.

Consideration should be given to extending the network into regional areas where commercial services are not available and not likely to expand into these areas. Facilities and people in regional and remote areas are generating increasing amounts of data of potential interest to researchers working in areas such as precision agriculture and resource management. Without appropriate network access the value of this data may not be fully exploited.

Access and Authentication

Australia's access and authentication infrastructure should be extended further to provide additional access to international researchers, where possible. Connecting the AAF to the rest of the world is the next step for Australia's national authentication service for research and education. Implementation will connect Australian researchers with their counterparts across the globe, and allow international collaboration partners to access Australia's national research infrastructure.

Australia's ongoing participation in the global initiative eduGAIN[20] will progress international access for researchers and make international collaborations much easier. This should include consideration of both authentication and authorisation.

Integrated Data-Intensive Infrastructure

Australia has the opportunity to consolidate the gains of the past decade and create a more integrated, coherent and reliable system to deal with the various needs of data-intensive, cross-disciplinary and global collaborative research. An Australian Research Data Cloud would build on existing eResearch infrastructure to create a cohesive, seamless experience for researchers that provides a fully integrated system.

The Australian Research Data Cloud should broadly align with the European Open Science Cloud and other global initiatives. It should support research data management from creation and discovery, through description and provenance, integration and storage, manipulation and analysis, and preservation. This improves the quality, reliability, durability, and accessibility of data, ensuring the outputs of research are more transparent. It should provide digital platforms that meet specific research requirements and integrate other data rich research infrastructure. It should support the sharing of informatics and software techniques to enable the deployment and wide use by researchers.

The underpinning Australian eResearch infrastructure should include cloud computing, HPC, networks, access, authentication and trusted data repositories. Data, collaboration and software services, skills and knowledge provided by the Australian Research Data Cloud will be an essential part of the new system.

Table 3: Priority Areas for National Research Infrastructure - Digital Data and eResearch Platforms

Elements	NRI Response
Tier 1 HPC	Enhance existing national HPC – NCI and Pawsey. Explore governance integration of these Tier 1 high performance computing facilities.
Create Australian Research Data Cloud	Enhance existing capability through the integration of existing capability – ANDS, NeCTAR and RDS to establish an integrated data-intensive infrastructure system, incorporating physical infrastructure, policies, data, software, tools and support for researchers.
Research networks	Enhance the capability and capacity of the AREN.
Access and authentication	Enhance capability and international relationships in access, authentication and authorisation services.

[20] eduGAIN simplifies access to content, services and resources for the global research community. http://www.geant.org/Services/Trust_identity_and_security/eduGAIN/

2.2 Platforms for Humanities, Arts and Social Sciences

This national research infrastructure focuses on enabling inquiry across the research spectrum including research into cultures, communities, environments, health and social well-being. Humanities, Arts and Social Sciences (HASS) platforms range from physical collections across the humanities, arts, environmental and medical sciences to online portals that facilitate the digitisation and digital access to original artefacts, materials and knowledge. In addition, HASS based platforms can be used to manage and integrate data to enable the development of solutions for complex social problems for the benefit of all Australians.

Future Directions

The opportunity exists to accelerate the impact of HASS research through a single platform that will make dispersed data sets more easily accessible. This platform will build on the foundations of institutional-level research infrastructure capabilities and bring holistic insight into society and its functioning. Specifically, this will improve the overall coordination of research infrastructure supporting access to physical and digital collections through enhanced digitisation aggregation and interpretation platform processes. The harmonisation of platforms for Indigenous and other cultural research purposes also supports this broader endeavour.

What we have

There is significant institutional level research infrastructure across the HASS sector. Only relatively small-scale national research infrastructure currently exists.

Collecting Institutions

National, state and territory collecting institutions house unique and irreplaceable items and materials that are necessary for undertaking cross-disciplinary longitudinal studies. These vast collections and holdings cannot be maintained by a single institution. As such, physical collections should continue to be categorised and preserved across a number of institutions – not doing so could undermine the valuable work of these institutions and research communities.

Digitisation of Collections

Collecting institutions are digitising their collections and capturing born-digital data for research purposes. Rates of digitisation vary, but on the whole only a small proportion of existing artefacts and specimens have been digitised.

Platforms for Indigenous Research

There are a number of existing platforms that support research into Indigenous health, social well-being, culture, language and history. Institutions and platforms such as the Australian Institute of Aboriginal and Torres Strait Islander Studies (AIATSIS), the Pacific and Regional Archive for Digital Sources in Endangered Cultures (PARADISEC), the National Centre for Indigenous Genomics (NCIG) and the Aboriginal and Torres Strait Islander Data Archive (ATSIDA) all use types of community consent and access control infrastructure. These controls allow Indigenous communities to access and selectively release their data to individual researchers. A similar process also allows digitised materials to be repatriated to Indigenous communities.

These consent processes comply with best practice guidelines for the use of culturally sensitive materials for research. Other platforms such as AURIN also use consent controls to regulate access to integrated geospatial data sets that are mapped, tracked and updated over time. This national platform supports the development of policy across a range of topics including transport, community safety, and health and Indigenous affairs. However, despite their important functions the various Indigenous research platforms are not interoperable and in some cases difficult to access.

What we need

Coordination and Integration for a Singular HASS Platform

Platforms for HASS include a range of research infrastructures that are expanding beyond single disciplinary research approaches and leveraging existing portals and facilities such as the National Library's Trove and the ALA. The integration of existing HASS platforms needs to be supported along with the use of digitisation and next generation technologies. This integration enables improved multidisciplinary approaches that increasingly underpin the HASS sector. To fully realise the potential of current research infrastructure for the humanities, arts and social sciences, a number of platforms should be enhanced and incorporated into a single platform to leverage future research needs that demand increased discoverability, accessibility and the utilisation of innovative technologies.

Improvements to existing research infrastructures are occurring incrementally and it is vital that this important work be continued by the relevant institutions. Focus on national investment would provide additional benefit and bring institutional capabilities collectively up to the level of national scale research infrastructure.

Enhanced access to national and state collections will be critical for future HASS research. This should include a greater degree of interoperability across all collecting institutions. In addition, the unique and ongoing role of these institutions needs to be recognised as collective national research infrastructure. Supporting these facilities also provides opportunities for researchers by improving access to the physical items in old and new collections. Accessibility of collections will be changed through the use of technologies such as digitisation that alters the way researcher's access collections across the country. Subsequently, there is an imperative to improve the accessibility to physical items and build on digitisation efforts that are shaping the nature of HASS research.

There has been significant effort and institutional investment in developing the process and undertaking the digitisation of materials. Trove and ALA have been instrumental in leading much of this work. Australia needs to coordinate access to the digitisation of collections and ensure that existing platforms and digital collections are interoperable domestically and internationally. One solution is to establish a digitisation excellence capability that could help coordinate the use of digital technologies and digitisation techniques.

Any current or future digitally based capability should be designed to be interoperable with leading international digital collections such as Europeana and draw on best practice for digital collections such those developed by the Smithsonian. Interoperability with these international collections facilitates open data, provides researchers access to Australian diaspora information and enables Australia to help shape international research infrastructure.

Harmonisation of Platforms for Indigenous Research

Improved integration and coordination across HASS should include the harmonisation of platforms for Indigenous research. A platform that can leverage Australia's cultural assets is needed. Creating a cohesive platform that harvests information, that is interoperable, and that provides appropriate levels of accessibility for communities and researchers alike is required. This platform will require community consent and access controls for Indigenous and other culturally and linguistically diverse (CALD) communities. Enabling CALD communities to access their history and information on the same level as Indigenous communities recognises Australia's diverse multicultural richness.

Integration of Social Sciences Data into the HASS Platform

A number of disparate and non-standardised large data sets exist across many social science disciplines such as psychology, sociology and political science. Countries such as the USA have made significant successful investments in harvesting and re-using data for multiple research purposes has expanded data use and improved impact.

A platform that brings together multiple data sets from social science disciplines will have the ability to harvest and re-use data for research purposes. An integrated HASS data platform will enable the Australia research community to leverage existing data sets and ensure multi-use and cross disciplinary research.

Table 4: Priority Areas for National Research Infrastructure - Platforms for Humanities, Arts and Social Sciences

Elements	NRI response
Integrated and coordinated HASS platform	Explore integration of networks for coordinated access to physical collections and digital materials enabling the digitisation of priority specimens across all collecting institutions. This could include the sharing of digitisation infrastructure and standardisation of best practice for processes and interoperability with international research infrastructures.
Harmonised platforms for Indigenous research	Explore integration of existing institutional level capabilities across a range of data platforms: AIATSIS, ATSIDA PARADISEC, NCIG and AURIN linked to wider platform for integration across all digital collections and portals.
Harmonised platforms for social sciences research	Explore integration of social sciences data from multiple sources together with tools for analysis and visualisation. This should be linked to the broader integrated and coordinated approach to a HASS platform.

2.3 Characterisation

This national research infrastructure area focuses on the characterisation of the structure, chemistry and physical properties of samples at the molecular level. Characterisation incorporates imaging, spectroscopy and scattering processes and includes studies of morphology, dispersion, structure, composition and bonding. As such, characterisation is critical to many areas of research including biological, biomedical, chemical and physical sciences. The research infrastructure associated with characterisation is diverse, requiring both small and large scale instruments to enable inquiry into samples of all forms and sizes.

Future Directions

Characterisation uses technologies to enable a number of key research areas. For example, advanced microscopy and microanalysis underpins modern science, medicine, engineering and industrial innovation. It provides diverse toolsets to explore the structure, chemistry and functionality of natural and synthetic systems to drive blue-sky research and solve applied industrial and translational problems.

Over the next five years emerging areas of characterisation will include: atomic scale microscopy; cryo-electron microscopy; multimodal imaging; high sensitivity microanalytical tools; high field, high resolution pre-clinical biomedical imaging; advanced synchrotron beamlines and nuclear magnetic resonance (NMR) technology. Access to these capabilities is crucial for Australia to maintain a world-leading position in a number of nationally significant fields of research.

What we have

Microscopy

The Australian microscopy and microanalysis landscape is wide and diverse. Most major research institutions house at least one microscopy facility and many institutions host high-end flagship instruments that are globally unique. Some systems are openly accessible whilst others exist to serve specific research efforts.

Australian Microscopy and Microanalysis Research Facility (AMMRF) is a national network of collaborative nodes and is a world-best practice model for access to a broad range of microscopy and microanalysis instruments and specialised staff. Participating institutions make over $200 million worth of instrumentation accessible to all researchers, both within and outside the AMMRF network. Institutionally-based microscopy centres complement national investment.

Biomedical Imaging

Biomedical imaging facilities include pre-clinical PET, MRI, SPECT and CT instruments largely for biological analysis (including plants, small animal, large animal and preclinical human studies), and access to cyclotron capabilities for the production of PET tracers. NIF provides state-of-the-art imaging infrastructure across 10 nodes across Australia. ANSTO supports imaging through the preliminary development of cyclotrons for the production of novel tracers.

Australian Synchrotron

The Australian Synchrotron is used across a number of areas including: health, materials, minerals, manufacturing, food security, the environment, national security and energy. The Government, under the NISA, set aside $520 million for operational costs to 2025-26 inclusive. This funding is predicated on collaborative funding of $100 million for beam lines to increase the Synchrotron's capabilities and to service an expanded range of users.

Visualisation and Modelling

The Australian imaging community has successfully coordinated several key informatics initiatives – MASSIVE for image processing and visualisation, NeCTAR for virtual laboratories, RDS for image publication and NIF for informatics. Over 50 instruments have been integrated with cloud-based data management software, automatically capturing, managing and delivering data to the cloud for processing, analysis and visualisation. This enables large scale analysis that increases our understanding of a range of materials and biological systems.

What we need

Microscopy

The next stage for microscopy research infrastructure should include: cryo-electron microscopy, new generation atom probe tomography and ion beam mass spectrometry. The existing AMMRF network should be expanded to include these new technologies, including those being developed in institutions currently outside the AMMRF. Such an approach will maximise the benefits of new science such as microprobes, while support is phased out for older technology. The new network should be national in nature and capable of servicing the needs of researchers across Australia.

For cryo-electron microscopy instrumentation, a national approach is also needed to support structural biologists. A national network of mid-range machines can be used for sample optimisation and initial characterisation, to identify suitable samples to be examined on openly accessible, state-of-the-art instruments. A national approach would address the significant data management challenges associated with new microscopy capabilities.

Biomedical Imaging

Australia needs to maintain state-of-the art large and small bore MRI with a focus on hybrid dual modality imaging such as PET-MR, scanners and next generation PET imaging. There is an opportunity for Australia to be at the forefront of imaging technology by joining the EXPLORER consortium. This USA led consortium is developing a new generation of PET technology capable of acquiring tracer kinetics from all tissues of the body at very low doses of ionising radiation enabling multi-disciplinary research to address major health challenges such as diabetes, mental illness and other complex multi-organ diseases. The low radiation dose will open up PET research to new groups such as pregnant women and children.

To support biomedical imaging, institutional level cyclotrons should be networked to increase the benefit of existing infrastructure and reduce duplication. This would provide an opportunity to develop unique radiotracers at each site improving and integrating biomedical imaging and research.

Nuclear Magnetic Resonance (NMR)

Institutional level NMR facilities are available across Australia. Networking these into an integrated advanced spectroscopy capability would enhance future capacity particularly around the acquisition of ultrahigh field NMR.

Neutron Scattering, Deuteration, Beam Instrumentation, Imaging and Isotope Production

Neutron optical devices can now deliver only those neutrons that are required for a particular application, leading to more detailed information. The next phase for neutron scattering should capitalise on advances in neutron beam instruments that may lead to the world's first neutron microscope. This unique instrument will permit the visualisation of liquid layers of oil and water within sand and rocks, at the micrometre level, providing information of vital interest to the mining and oil industries.

New specialised instruments to produce wholly or partially deuterated samples will expand Australia's ability in this field. Researchers will be equipped to study and better control self-assembly for the structural characterisation of fibres, whether biological or synthetic.

Australian Synchrotron

The potential enhancement of the Australian Synchrotron through the addition of new beamlines will give researchers access to the specialised tools and techniques to undertake critical research. The new beamlines will enable high-energy three dimensional imaging, high throughput protein structure analysis with small crystal capacity, and residual stress analysis using combined spectroscopy, diffraction and imaging. This will deliver better use of resources, novel and more targeted therapies, and improved materials.

Access to Accelerators for Imaging

Maintaining current research infrastructure such as the Australian Synchrotron and the Heavy Ion Accelerator (HIA) will be critical for future development and ensuring Australia can also pursue international accelerator opportunities. Imaging is a rapidly evolving field and while hardware can be upgraded, it may be effective to share systems as they become available. Leveraging existing national-scale and landmark accelerator investment provides a range of imaging technologies essential to service the needs of the research sector.

Table 5: Priority Areas for National Research Infrastructure - Characterisation

Elements	NRI Response
National network of microscopy and microanalysis	Enhance capability through next generation technologies such as those in AMMRF.
National network of biomedical imaging	Enhance capability through next generation technologies in NIF and the Australian Synchrotron and ensure an effective network for existing institutional level cyclotrons for the production of radiotracers.
Neutron scattering, deuteration, beam instrumentation, imaging and isotope production	Maintain priority for current facilities such as OPAL, including the OPAL development plan and the NDF.
Synchrotron capability	Enhance capability through the expansion of next generation technologies in the Australian Synchrotron (new beam lines).
Accelerators for imaging	Maintain priority for the Australian Synchrotron and HIA and explore international opportunities.

2.4 Advanced Fabrication and Manufacturing

This national research infrastructure area enables the synthesis of advanced materials, fabrication of devices and development of prototypes, including at the micro and nanoscale, for a broad range of research and industry applications, including medical, biological, energy, advanced manufacturing and defence sectors.

This includes the development of processes to manufacture new classes of materials, objects and devices to create proof-of-concept and prototype products.

Future Directions

Australia's world leading research programs in quantum computing, advanced materials and photonics rely on access to cutting-edge fabrication infrastructure. Applications for the research are diverse and include advanced sensing, communications, energy capture and storage, water treatment, and new medical treatments, diagnostics and disease prevention.

Future directions in fabrication research will be driven by the convergence of disciplines. Bioengineering, the fusion of engineering with life sciences, demands the development of new fabrication techniques. Examples include microfluidic and lab-on-a-chip devices, and the ability to successfully and accurately place living tissue, including cells, gels and fibres, into a single construct using 3D printers. 3D cell printing will provide new models, including exploration into the treatment of neural diseases.

The integration of wireless technologies with bio implantable devices (WiMed), autonomous systems and the Internet of Things (IoT) are underpinned by smart sensing technologies. Also, next-generation photonic devices for advanced communications require the integration of optical components on silicon chips.

The breadth of this research will be supported by continued investment in flagship and mid-range suites of fabrication equipment across a network of specialised facilities.

What we have

Fabrication of Materials and Devices on a Micro and Nanoscale

Access to infrastructure to synthesise advanced materials, fabricate devices and develop prototypes, including at the micro and nanoscale is fundamental to all NSRPs and the commercial opportunities that flow from them. These have driven advances in areas as diverse as medical, biological, renewable energy and defence.

The fabrication of complex structures at the cutting-edge of materials science allows researchers to test fundamental physical and chemical theories, and to build prototypes of new devices for commercial development. This is currently provided by the ANFF and can be enhanced by a capital refresh of existing, ageing and obsolete equipment.

The ANFF is a collaborative network linking facilities across 19 Australian universities providing researchers with access to a portfolio of over 500 tools and a cohort of expert technical staff. A number of new Australian start-up companies in areas ranging from medical devices to the resources sector have been supported by ANFF.

Fabrication, particularly nanofabrication, requires co-location with relevant microscopy and analysis tools for effective use by researchers. This use is different to that of specialist characterisation facilities.

Chemistry and High Throughput Screening Processes

High throughput screening processes for early drug discovery and other areas of research has become increasingly important to chemists and biologists. Rapidly identifying errant results and false positives can dramatically increases the productivity and efficiency of research. Existing institutional research infrastructure largely meets the needs of researchers in this area.

Additive Manufacturing and Deposition Printing at a Range of Scales

Additive manufacturing is a major disruptive technology taking root in manufacturing and is anticipated to transform existing approaches. Additive manufacturing encompasses activities such as 3D printing, printing in metals, organic electronics, ceramics and other functional materials, at a range of scales and dimensions. Entry level tools are widely available. High-end manufacturing capabilities for metals are available through facilities such as Lab22 at CSIRO and several universities.

Bioengineering and Bio Fabrication

Current Australian strengths in bioengineering and bio fabrication have led to developments such as the BioPen, which allows surgeons to draw stem cells directly onto damaged cartilage for self-repair, and the Vaxxas Nanopatch™ needle-free vaccine delivery. The development of these devices has relied on access to national research infrastructure. Microfluidic and lab-on-a-chip devices have been developed for high throughput and high sensitivity screening and sensing applications.

What we need

Future research infrastructure for advanced fabrication and manufacturing must enable novel materials development, new and hybrid device fabrication techniques, and the integration of devices and systems to create industry-ready prototypes.

Fabrication of Materials and Devices on a Micro or Nanoscale

Support for fabrication of materials and devices at the micro and nanoscale requires continued investment in flagship and mid-range suites of fabrication equipment across the national network. This will provide breakthroughs in new classes of materials, accelerate technology development and prototyping of products. Increasingly, interfacing nano-biotechnology with nano-electronic or nano-photonic components at different scales, and being able to connect the nano to the micro to the macro scale, will underpin research outcomes. The current ANFF has capacity for expansion to accommodate new technologies and emerging research requirements within its existing network of specialised technologies.

There is an important role for the physics community in developing advanced instrumentation and precision equipment. While needs are largely being met through existing national and institutional research infrastructure, it is vital that opportunities for collaboration between the materials science and physics communities are enhanced through existing networks.

Engineering to Deliver, Package and Integrate New Classes of Fabricated Devices

Support for the translation of research into high impact outcomes requires the ability to fabricate advanced materials and devices and take these from laboratory proof-of-concept to full prototypes.

This requires larger scale fabrication and testing facilities in a range of different environments to meet the needs of nano-electronics, nano-photonics and bioengineering applications. Areas of high national significance that would benefit include quantum computing, medical devices and environmental monitoring.

Research on next generation photonic devices for applications including astrophotonics, advanced telecommunications and quantum sensing, requires the fabrication of fully packaged prototypes. Advanced optical device fabrication must support integration of hybrid photonic devices with custom bulk optics and provide facilities for fabrication of specialised multi-layer optical coatings. Increasing Australia's limited capability in packaging would significantly reduce costs and development times, increasing the production of devices suitable for use as commercial prototypes.

Bioengineering and Bio Fabrication Capacity

Bioengineering applications require biomaterials development to be seamlessly integrated with emerging customised fabrication capabilities and clinical applications. Next generation devices and products include sensors for medical diagnosis and health monitoring, and implantable structures to address clinical challenges such as tissue regeneration.

A translational facility at appropriate scale and with good manufacturing practice (GMP) traceability is required to support the development of materials, 3D structures and medical devices. Consideration and active engagement in regulatory frameworks for the emerging bio and nano-engineering must underpin the facility. Facilities for integration and pre-commercial production and testing to take a prototype manufactured under GMP conditions through to a test product suitable for clinical trials would provide a valuable platform for Australia.

Table 6: Priority Areas for National Research Infrastructure - Advanced Fabrication and Manufacturing

Elements	NRI Response
Fabrication of materials and devices on a micro or nanoscale	Enhance capability in fabrication in ANFF through next generation equipment.
Bioengineering and bio fabrication	Enhance capability in GMP facilities to enable the full bio-fabrication pathway from bench to clinic.
Engineering capability for new classes of fabricated devices	Enhance engineering capability in the ANFF.

2.5 Astronomy and Advanced Physics

This national research infrastructure area focuses on the understanding of the fundamental physics of the universe and its application to support research. Through this capability we can: enhance our knowledge of the origins and evolution of galaxies, stars and planets; probe the physics of extreme environments; gain a deep understanding of the fundamental forces and forms of matter and energy that make up the universe; and study the building blocks of life that underpin most aspects of modern society including engineering, technology and medicine.

New and emerging research areas such as quantum technologies, astronomy and advanced physics increasingly require access to larger scale, complex and sensitive instrumentation that is global in nature and operated by international partnerships and consortia.

Precision measurement is becoming increasingly important with the rapid development of quantum technologies and will become vital over the next decade.

Future Directions

Australian researchers will continue to break new ground in astronomy and advanced physics research underpinned by strategic investments in domestic and international capabilities building on existing areas of strength. Astronomy will be supported through an integrated and strategic platform across optical and radio astronomy with access to the necessary eResearch capabilities. Similar to astronomy, targeted investments will position Australia as globally competitive in quantum capabilities and instrumentation. Strong foundations in mathematics skills will remain a cornerstone of Australia's position as an astronomical nation.

What we have

Astronomy

While Australia has a strong capability in astronomy and related instrumentation, we are entering an era where the facilities required to underpin astronomy are too large for any one nation. Global facilities are built in places where geographic and other considerations allow the best possible performance to be achieved. In radio astronomy, Australia has one of the world's best radio-quiet sites in Western Australia. Equivalently, high-mountain sites overseas provide the best observation conditions for the largest optical telescopes. International arrangements are necessary to access overseas facilities for optical and radio astronomy. Australia's ability to play a leading role in major global astronomy projects is built on human capital and international reputation in key areas of astronomical science and instrumentation.

The precursor and pathfinder telescopes, the ASKAP and the MWA, provided by the Australian Telescope National Facility, have increased Australia's ability to be an active contributor in the SKA consortium.

Australia's high standing in astronomy research is built on access to the best optical astronomy observatories, at the very large and mid-tier scales. The GMT, is the first of the next generation of Extremely Large Telescopes that observes at optical wavelengths. Australia is building key scientific instrumentation as part of its contribution to the GMT. Australia's current capability in optical astronomy is provided through access to overseas eight-metre-class optical telescopes through short-term agreements with the Keck, Magellan and Gemini Observatories. This provides limited access with the ability to influence governance and long-term planning.

Gravitational Wave Discovery

The first direct detection of gravitational waves was a major milestone for the scientific community. Australian scientists played important roles in this achievement, developing instrument technologies and search methods as members of the Laser Interferometer Gravitational-Wave Observatory (LIGO) scientific collaboration. Australia was one of the four partner countries who funded, delivered and installed components on the second-generation Advanced LIGO detectors in the USA which made the discovery. Australian leadership in this area has been recognised through the ARC Centre for Excellence for Gravitational Wave Discovery placing Australia at the forefront of gravitational wave astronomy.

Nuclear and Accelerator Facilities

Nuclear facilities fall into two classes – those based on particle accelerators and those based on reactors. These facilities are essential to multi-disciplinary communities and researchers in Australia and internationally. Internationally, ANSTO has connections to consortia of research reactors, neutron beam facilities and synchrotron light sources. These networks allow us to retain and grow our capacity to develop and enhance the facilities to support the user community.

Accelerators

The broad accelerator science field encompasses both the development of the facilities and instrumentation, and the application of the particles and photons that are used to characterise materials and systems. Examples in Australia include cyclotrons, mainly for the production of radioisotopes, synchrotrons which produces light in wavelengths from infrared to hard X-rays, and heavy ion accelerators used in mass spectrometry applications. These facilities are used to characterise a large variety of matter.

There are currently specialised nodes supporting accelerator science in Australia, including the Heavy Ion Accelerator (HIA), the Australian Synchrotron and the Centre for Accelerator Science. These serve a variety of users and applications and maintain connections to the international community. The HIA is also used for nuclear physics research and is networked with other nuclear physics accelerators internationally.

Particle Therapy

An emerging area of treatment and research internationally, particle therapy uses protons or carbon ions to treat solid tumours. The protons or carbon ions are formed into a beam in a particle accelerator, which when not being used for patient treatment is available for use in advanced physics research. Such research is a capability area that should be investigated in the future.

Reactors

Australia has a landmark multi-purpose reactor, OPAL, which provides user access to neutron beam instruments and specialised irradiation facilities. The future requirements are explored in the Characterisation Focus area.

The National Deuteration Facility (NDF) underpins studies that show the position of lighter atoms in protein structures. The NDF is a feeder facility for applications in neutron beam instruments. It also offers opportunities for specialised applications in the pharmaceutical industry.

Australia maintains linkages to the ITER fusion reactor in France by a direct technical cooperation agreement and through a number of scientific committees at the International Energy Agency (IEA) and the International Atomic Energy Agency (IAEA).

Quantum Technologies and Capabilities

Australia has a vibrant capability in quantum research, with Centres of Excellence in nodes across the country. Quantum technologies have been identified by the United Kingdom and the EU as key areas of growth in future industries such as quantum computers, timing devices, gravity sensing devices, positioning systems, secure communications and enhanced imaging.

Precision Measurement

The ability to design, develop and build scientific instruments is an internationally recognised strength of Australia. The development of new characterisation techniques, currently unavailable commercially, provides Australian industry with a competitive advantage in global markets. Australia is active in areas spanning space research, quantum technologies and high-precision bio sensing applications such as neural imaging.

In addition to quantum computing, quantum effects are also being harnessed to develop precision sensors, providing increased sensitivity and lower energy consumption than traditional devices. Advances enabling quantum sensors to operate at room temperature open up a range of new applications including geological surveying, lab-on-a-chip chemical analysis and magnetic anomaly detection. Next generation quantum sensors will provide imaging technologies with the ability to observe cell function at the molecular level, enabling future breakthroughs and advances in nanomedicine, as well as drug testing and development. The technology has developed to the point where commercialisation of a range of quantum sensors will occur in the coming decade.

The ability to reference new precision measurement techniques to international standards is important for future research needs, especially with the increased focus on quantum technologies. The NMI is Australia's peak measurement body and provides national leadership for key metrology issues. Some capacity to develop and fabricate components for new measurement instrumentation is currently provided at the national level through the ANFF.

What we need

An Integrated Approach to Astronomy Infrastructure

A weak link in the current national astronomy infrastructure portfolio is lack of access to the largest optical and infrared telescopes. Partnership with an eight-metre-class optical telescope will be necessary for Australia to continue to have the scientific expertise and technical capacity to conduct world-leading science with the GMT (a multi-mirror optical telescope equivalent to a 22 metre single-mirror optical telescope) when it comes online and maintain the nation's leadership in instrumentation.

This partnership will allow Australia to maintain and develop the required expertise and technical capacity in optical and infrared astronomy to maximise its significant investment in the GMT. This will also provide opportunities to build on Australia's strength in instrumentation development for radio astronomy. These will enable Australian industry, with expertise in enhanced instrumentation, to be in a stronger position to bid for design and construction contracts.

Astronomy is a data and computational-intensive discipline. This will accelerate in the next decade as new telescopes come online, generating unprecedented data volumes that will require significant HPC time for data processing and modelling. For example, the SKA project will generate unprecedented volumes of data. This will demonstrate Australia's international leadership through the development of underpinning infrastructure and expertise to deal with the data flow and science processing.

Australia's continued status as an astronomical nation is contingent on access to cutting-edge optical and radio telescopes, bolstered through computational and theoretical astrophysics. Significant investment in the SKA and GMT will provide the nation with access to the next generation astronomy infrastructure vital for new discoveries.

The current distributed approach to astronomy infrastructure involves multiple organisations with separate responsibilities for discipline specific research infrastructure. An integrated governance structure should facilitate a "team-Australia approach". It should include the critical mass necessary to effectively and efficiently engage with billion-dollar international facilities such as the SKA and GMT, and mid-tier international infrastructure, in addition to providing a coherent approach to existing domestic research infrastructure.

Gravitational Waves

Australia is geographically well placed for a third generation gravitational wave detector that would optimise the resolution of the entire world array. Australia's involvement in a third-generation array, through access to international facilities, or as host, possibly through an international consortium, should be explored in the future. Gravitational wave research will provide significant flow-on benefits for our highly technical, advanced manufacturing industry that will underpin the development and construction of a third generation array, regardless of its location.

Precision Measurement

It is increasingly important for many fields of research to employ precision measurement – for example optical and microwave sources having extremely high frequency stability for high impact experiments. These include direct measurement of Einstein's time dilation effect, as well as frequency references for new atomic clocks, optical and radio astronomy and radar applications – significant for Australia's involvement in the SKA and GMT.

New quantum technologies will provide new observational techniques with flow on effects for new technologies such as the development of quantum optics used for gravity wave detection. Future needs include improved capability for emerging sensors based on quantum, bio and nanotechnologies. These will require new supporting infrastructure to take full advantage of emerging technologies.

Future precision measurement research will require ultra-low background radiation laboratories for experiments in the fields of biomedicine, advanced physics, materials science and geophysics. The

Stawell Underground Physics Laboratory could provide national capability for ultra-low background radiation experiments across a wide range of disciplines.

The capacity to develop bespoke instrumentation is a critical next step to commercial exploitation by instrument manufacturers in future technologies. Existing capability in areas where Australia possesses expertise in instrumentation development should be supported to continue and expand into new domains, such as space-based instrumentation. New space-based instrumentation will require space-qualified, accurate and reliable measurement technologies, such as methods for interferometry in development for the GRACE mission in a collaboration led by the ANU and supported by NMI.

Enhancing Australia's Nuclear Capability

The next phase of development for neutron scattering facilities at the OPAL reactor would be the development of the second beam hall. The development of a neutron delivery systems will allow the development of instrumentation for equipment that can place samples in extreme environments such as those experienced during industrial processes or in the centre of planets. This capability will allow us to develop new materials and processes to address issues in energy, environment, and health. Further, it will provide a new understanding of the structure and dynamics of the Earth's crust and upper mantle, knowledge that is crucial if we are to predict and mitigate natural disasters, reduce the impact of human activity on the environment and locate and exploit natural resources.

Table 7: Priority Areas for National Research Infrastructure - Astronomy and Advanced Physics

Elements	NRI Response
Astronomy infrastructure	Enhance capability in optical astronomy and associated technologies by establishing a formal partnership in an eight-metre-class optical telescope, to maximise return on our investment in the GMT. Maintain priority through full utilisation of the SKA precursor telescopes (ASKAP and MWA) to maximise the Australian benefit via technology development and scientific discovery during the construction of the SKA.
International accelerator programs and instruments	Maintain priority and continue to increase our memberships to international accelerator facility consortiums, groups and institutions.
Precision measurement	Explore establishing a precision measurement capability to support advanced manufacturing, quantum measurements and enhanced traceability in biological and natural systems, with expansion to provide expertise in quantum measurement.
National nuclear facilities	Enhance neutron beam capability at the OPAL reactor through additional beam capacity (second Neutron Beam Guide Hall) for research, medical needs and for national sovereignty and global engagement.

2.6 Environmental Systems

The focus for this national research infrastructure area is on integration of observations, predictive modelling and uncertainty assessments, for a broad range of research and industry applications. Benefits will be realised through increased knowledge, enabling timely adaptions to changes in environmental systems.

Integrating existing and new high spatial and temporal resolution data with analysis and predictive modelling will establish a national integrated Environmental Prediction System. Enabling environmental prediction, founded on robust observations and with measures of reliability, is critical for decision makers to manage the health of the future environment, economy and population.

Future Directions

National research infrastructure to integrate observations with predictive modelling will provide strong evidence based advice to boost our economy through improved environmental and risk management, primary production, and resource development and water management while sustaining biodiversity. Predicting impacts on environmental systems will underpin strategic decisions for the management of our continent and surrounding oceans including the development of early adaptions to climate change for domestic and global sustainable growth. Australia can benefit from its unique geographic, economic, intellectual capabilities and secure environment to become a global leader in integration of observations, modelling and prediction systems across environmental systems that will maximise innovative economic opportunities and increase our national wellbeing and quality of life.

What we have

Marine Understanding

Australia has demonstrated global leadership in: Antarctic research for a century; sustained observation of marine systems through investment in IMOS; and complementary infrastructure including vessels such as the RV Investigator and the RV Solander. This research infrastructure has led to increased national and international collaboration across a broad range of marine research.

IMOS and its collaborating partners are at the forefront of developing new monitoring technologies using advanced sensors and real time integration of data into modelling suites. The National Science and Research Priorities and the decadal National Marine Science Plan highlight the need for enhanced observation and modelling capability to address challenges in energy security, environmental change and predictions of the ocean state for defence, industry and government needs. Australia derives considerable economic, social and environmental benefits from the marine environment, through our research infrastructure assisting marine industries, maritime defence, coastal ecosystem services, climate and weather and marine biodiversity.

The Australian Antarctic Program includes major national research infrastructure that supports high latitude climate observation. These observations improve our climate models by understanding past climate and climate drivers, as well as sea level rise. Australia maintains unique Antarctic scientific expertise and infrastructure, such as research stations, laboratories and vessels. For example, the new icebreaker vessel will be globally the most advanced research and resupply vessel.

Australia's Marine National Facility (MNF), which includes the National Environmental Tracing Facility and the National Ice Core Archive, provides valuable ice core data for understanding our climate and supports scientific investigations under the Antarctic Treaty system.

The AIMS Sea Simulator is an important marine research aquarium facility for tropical marine research allowing significant research not previously possible in Australia or internationally. Expanding access to the Sea Simulator will increase understanding of Australia's tropical marine organisms. Other examples include the CRC for Developing Northern Australia has identified opportunities for business and growth in the north focusing on agriculture, food and tropical health.

National research infrastructure underpins leading Australian environmental research in ARC Centres of Excellence and CRC. The ARC Centre of Excellence for Coral Reef Studies has multi-disciplinary research teams examining reefs dynamics to increase our understanding of reef resilience. The CRC for Antarctic Climate and Ecosystems provides seven highly integrated research projects aimed at understanding the changes to Antarctica and the Southern Ocean and the impacts on the marine ecosystems. ARC Centres of Excellence such as the Climate System Science and the Climate Extremes enhance Australia's climate understanding and modelling particularly at regional scales, minimising Australia's economic, social and environmental vulnerability to climate change.

Case Study - Australian Antarctica Science Strategic Plan 2011-12 to 2020-21

The plan demonstrates the environmental importance of Antarctica and how strategic investment approaches are incorporated into planning. The plan establishes the framework for Australian Antarctic research that universities, research institutions, the Australian Antarctic Division (AAD) and other national and international government bodies contribute. It is an exemplar of Australian and international research that is entirely supported by large infrastructure where up to 28 collaborating countries and close to 200 research institutions undertake research. The action plan includes building on Tasmania's infrastructure to be the premier East Antarctic Gateway for research.

Biodiversity

Australia requires a national ecosystem observatory capability to monitor carbon, water and biodiversity. This needs to be fully integrated, including modelling, to enable the prediction of future changes in carbon, water and biodiversity. This will enable the development of the capacity to understand, manage and predict the future of Australia environment, and how energy, carbon and water interact with vegetation and soils. The Terrestrial Ecosystem Research Network (TERN) facility provides important capability in this area, including observations used to calibrate remotely sensed data domestically and internationally. Australia's international contribution of calibration sites, techniques and analysis has enabled reciprocal access to global remotely sensed data and consequently an enormous increase in national capacity.

Open access to integrated biodiversity information combined with discovery, visualisation and analysis is critical to modern research. A key enabler is ALA which currently holds 63 million occurrence records, 1.2 million images, over 4000 data sets and 470 spatial layers. The informatics platforms developed by IMOS, TERN and ALA are highly regarded and increasingly adopted by other countries. ALA infrastructure, in collaboration with the Global Biodiversity Information Facility (GBIF), has been adopted by a number of countries for their national biodiversity portals (Atlas of Living Spain, Atlas of Living France, and Atlas of Living Scotland).

Agriculture

Agricultural advances are increasingly being realised through technology, on the farm through to transport logistics, and strong collaborations between researchers and industry. Research infrastructure is at the nexus of innovation in agriculture. Technological advances in the APPF enable research in plant behaviour to make better predictions on plant function and performance in different environments. These improvements boost productivity, lower production costs and reduce the environmental impact. Advances in the use of seasonal climate forecasting allow greater risk management in agricultural systems. Primary producers in northern Australia are using infrastructure in novel ways to combining food production and energy savings.

Earth Sciences

AuScope provides world-class research infrastructure for geospatial earth research. AuScope's spatial services have been adopted by 20 research organisations across Australia and its AuSREM model is used by NASA, GA and CSIRO.

Considerable earth science research is undertaken by a range of departments and organisations such as CSIRO and GA which provides technical advice to Government on geological, geophysical and geospatial issues. GA relies on having access to world-class infrastructure to discover new mineral and energy resources and secure Australia's water resources.

Fundamentals of eResearch

Environmental systems that integrate observations and modelling for predictions are dependent on eResearch capabilities such as data management and HPC. The Data Cube stores, organises and analyses large volumes of satellite imagery and other geospatial datasets at the continent scale. The Data Cube, a collaboration between Geoscience Australia, NCI and CSIRO, enables quick and easy organisation and analysis vast quantities of satellite imagery and other Earth observations.

In partnership the ARC Centre of Excellence for Climate System Science, BOM and CSIRO have integrated high performance data and computing to establish the Australian Community Climate and Earth System Simulator (ACCESS). Linked with major international research and operational facilities, ACCESS provides improved forecasting and climate projection with direct benefit to the Australian economy, business and government.

Case Study – Sustainable fisheries

MNF has been actively involved in leading the development of acoustic remote sensing to determining the population size and species on the coasts of Australia. The MNF Blue water research vessel and sophisticated scientific equipment have built an accurate picture of the population, habitat and eco-system status of key commercial fish species informing strategies and policy aimed at developing sustainable fishery management of high value species, as well as implementation of appropriately situated Marine Protected Areas. Techniques and methodologies developed on board MNF vessels have contributed to technology transfer to commercial vessels of echo sounding equipment to assist in ongoing population surveys and improved fishing efficiency. Sustainable fisheries provide valuable marketing advantage to Australian fisheries.

Renewable Energy

Existing institutional and industry research infrastructure largely meets the needs of researchers. The ARC Centre of Excellence in Exciton Science is developing next-generation energy and security technologies by manipulating light in unique ways. The Centre's research focuses on 'full-spectrum' photovoltaics through to printable electronics, energy-efficient lighting and displays, security labelling and optical sensor platforms.

There are a many centres of excellence in the environment area and in combination with research infrastructure significantly contribute to the research outcomes. For example, the CSIRO Manufacturing Flagship utilises the ANFF Micro and Nano Devices Laboratory to undertake research to support renewable energy developments.

What we need

Australia's has significant national research infrastructure that encourages and supports our global leadership in the Southern Hemisphere in environmental prediction. The following will secure our global leadership position over the next decade.

- Enhancing integration of existing data and mathematical modelling across large geographic areas, including remote and urban regions for prediction of change over time to enable early adaptation, planning and business development.
- Further develop remotely sensed data analysis given our unique geographic, economic and technical capabilities.
- Enhancing domestic instrument and sensor development, sensor networks and integration of new technology.
- Establishing the ACCESS modelling system as national infrastructure to align and deliver the next generation of products to business, government and for environmental management.

Australia's strong foundation of environmental observations needs enhanced data collection in key regions to improve understanding through more precise modelling. This can be achieved by harnessing data sources from industry, non-government sectors and state governments. Additional in situ and remote sensing is needed in Antarctica and northern Australia as well as in urban ecosystems where historical data is limited.

Increasing automation of sensors and imaging capability needs to be a priority. Autonomous, intelligent sensors are able to record biological and chemical measurements of marine biodiversity. Pairing satellites with UAVs and drones for high resolution observation, mapping, environmental and biodiversity analysis should also be explored.

International collaboration is critical in this area, especially where Australia relies on access to international data streams, such as satellite data. IMOS is also part of the international UNESCO network (though the Intergovernmental Oceanographic Commission) that formally recognises IMOS as a Regional Alliance of the Global Ocean Observing System.

The Australian Antarctic Strategy and 20 year action plan[21] includes investments in a new icebreaker, overland traverse capability and proposals for new aviation access. It also includes major unfunded research infrastructure needs, for example upgrading the research stations.

Marine Systems

A coordinated marine research fleet will enhance marine research from the coast to deep oceans including the tropics and Antarctica to enable Australia to fully realise the benefits of the blue economy, estimated to contribute $100 billion per annum by 2025.[22] This national research infrastructure should comprise integrated marine monitoring program and access to national research vessels, remotely operated and autonomous underwater vehicles (ROVs and AUVs respectively), and manned submersibles. For example, smart new sensors combined with autonomous systems will turbocharge our understanding of coastal and estuarine systems and reduce uncertainty as to the future impacts of planning and investments decisions.

Other research infrastructure could include increased drilling technology, borehole instrumentation the ability to drill to greater depths and additional vessels. These provide critical for data and information on marine environmental baselines and impacts, ocean conditions, petroleum and mineral resources, climate change, fish stocks, ecosystem effects of fishing and biosecurity threats.

Bringing genomic technologies out of the laboratory and into the ocean is exciting new research that is within our reach. Implementing a marine microbial observatory in Australian coastal waters would be a world first.

Increasing research sea time on vessels will enhance Australia's marine capability. For blue water research the RV Investigator should operate 300 days per year while the Aurora Australis has capacity to increase its operations outside winter time. For coastal research, the small and ageing coastal vessel fleet needs to be updated. Opportunities to share national and international vessel capacity should also be explored.

Terrestrial Systems

Terrestrial modelling and predictions rely on ongoing terrestrial ecosystem monitoring and observations. These should be enhanced through the integration of existing and new data streams that are coordinated, and where possible automated, across platforms. Next generation infrastructure sensors combined with remotely sensed data will support biodiversity management, sustainable use of natural resources and enable greater assessment, prediction, adoption and management. Any enhancements should consider the Australian Earth Observation Community Plan.[23]

An Australian environmental prediction system should combine new and emerging observations with innovative modelling to enable forecasting of future environmental change and the development of management response strategies. A future terrestrial environmental prediction infrastructure must leverage existing eResearch capabilities including NeCTAR, ANDS and HPC.

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[21] Commonwealth of Australia (2016), *Australian Antarctic Strategy and 20 Year Action Plan,*

[22] National Marine Science Committee (2015), *National Marine Science Plan 2015-2025; Driving the Development of Australia's blue economy*,

[23] Australian Earth Observation Coordinating Group (2016) *Australian Earth Observation Community Plan 2026: Delivering essential information and services for Australia's future*

Further development of ALA to include new data streams such as trait data, built environments data, integrated soils, vegetation, ecoinformatics, land use and water data can contribute to our knowledge, assessment, conservation and sustainable use of biodiversity.

Agriculture and Primary Production

Australian primary producers are utilising technological advances to improve productivity, across agriculture, aquaculture and fisheries and forestry. New sensors and associated networks provide increasing insight into the efficient use of land, water, nutrients and pesticides and will increase productivity.

Partnerships between the Managing Climate Variability Program, BOM and the Rural Research and Development Corporations have highlighted the value of seasonal climate forecasting. The ACCESS model should be re-engineered to enable researchers to utilise the model to increase productivity and reduce environmental impacts.

Research infrastructure such as the Digital Homestead[24] demonstrates how technologies can enable better decision making on farms, leading to improved productivity and profitability. Research infrastructure used by primary producers such as widespread and integrated sensor networks, virtual farms and shared web-based platforms will take these industry sectors to the next level. Benefits would include region-wide improvement in the economic position and stability of existing cattle stations, early adaptations to climate change, reduction of Australia's emission of carbon dioxide and precision application of nutrients to reduce nutrient run-off.

Access to technological advancements would provide useful information to a range of primary producers and could improve Australia's export industries and productivity.

Case Study – Prediction of weather and climate across scales

The first-ever shipborne observations of the vertical distribution of cloud properties and surface shortwave radiation over the Southern Ocean were made using the MNF RV Investigator on two voyages in 2015 and 2016. Using RV Investigator's suite of state-of-the-art meteorological instruments and laboratories allowed scientists to conduct an assessment of the ACCESS performance for the first time over the Southern Ocean, providing a clear path towards improvements in the model. New observations from TERN were used to assess and improve the representation of extremes and drought in the ACCESS model via both ocean and land data.

The ACCESS earth system model seamlessly links models of the oceans, atmosphere, sea-ice, land surface, global carbon cycle and chemistry, and aerosols, to simulate changes in the Earth's climate systems with ever-increasing accuracy. These models enable scientists to project major changes in the Earth's climate in the longer term, and to make short and medium-range weather forecasts and seasonal predictions for Australia. Next generation development and enhancement of these models are critical to Australia's future capacity to understand and predict extreme weather events such as tropical cyclones, bushfires and flooding, and for examining the benefits of strategies to manage water and carbon in the Australian landscape.

[24] The Digital Homestead project combines new and existing technology to provide holistic information for herd and property management.

Weather, Climate and Climate Variability

Accurate short-term, multi-week and seasonal forecasts and longer-term climate predictions enable primary producers and policy makers to make more informed decisions. These predictions are important to the risk management of extreme events, urban design, power infrastructure planning and water management. Ongoing investment in modelling systems, particularly ACCESS, will improve the accuracy of predictions and assist primary producers make informed decisions, increasing their profitability and strengthen rural communities.

Modelling systems such as ACCESS can improve the accuracy of predictions, assisting primary producers to make more informed decisions, increasing their profitability and the strength of rural communities. The scale of these models is now so large that they rely on international partnerships and a fully aligned national effort. A key challenge is to enable these models to be shared across the whole research community and efficiently integrate discoveries from overseas. Australian HPC and data modelling capability, provided through NCI, will open up new opportunities such as coupling existing modelling used in finance, agriculture, urban design and transport with models of climate variability.

Earth Systems

The success rate of minerals exploration is declining and this is leading to reduced international exploration investment. Understanding the Earth's crust (from water to energy to resources) requires characterisation of the deep Earth. This understanding will enhance Australia's capacity to supply the emerging demand for minerals and rare earths vital to innovative manufacturing.

The UNCOVER initiative works towards characterising the deep Earth. Australia needs to develop an integrated distributed network of geophysical and remote sensing and geochemical sampling and analysis that will form a geological telescope to support research. UNCOVER is a collaboration across Government, industry, academia and the Academy of Science. Increasing collaboration with existing national research infrastructure such as NCRIS will enhance our understanding of emerging geophysical energy issues, resource extraction, groundwater, agriculture production, urban development impacts and opportunities for CO_2 geosequestration.

Table 8: Priority Areas for National Research Infrastructure - Environmental Systems

Elements	NRI Response
Environmental prediction system	Enhance capability for new infrastructure integrated with eResearch to enable existing and new data with new technologies and modelling to build an Environmental Prediction System for Australia. Enhance capability to re-engineer weather and climate modelling (ACCESS) systems. Explore integration to build new infrastructure to automate the upload of data. Maintain priority for new biodiversity data streams to be integrated with existing environmental data platforms such as ALA.
Inward focused Earth monitoring and exploration	Explore establishing next generation Earth monitoring and potential development of inward looking telescopes. Enhance capability in AuScope to: include new Earth monitoring data; utilise new remotely sensed data and to visualise the findings.
Remotely sensed Earth observations	Enhance capability in remotely sensed data infrastructure, including sensors and sensor networks, and calibration sites across Australia.

Elements	NRI Response
	Enhance capability to serve a wide range of new and innovative remotely sensed products to the research community, business and industry in near real time.
Agricultural integrated networks	Explore integration of networked agricultural platforms based on next generation sensor data for a national approach to integration and modelling likely production across diverse geographical locations and under a range of climatic scenarios.
Marine Systems	Enhance ocean observing capability and development of next generation observing infrastructure, such as AUVs, ROVs, vessels and expansion of IMOS into estuaries and coastal waters. Enhance capability by increasing blue water sea time for the RV Investigator and Aurora Australis. Explore the potential to grow the national coastal research vessel fleet and increase access to AIMS vessels for collaborative research. Maintain priority for deep drilling infrastructure on land, ice and in deep oceans and ice core storage. Maintain priority for Antarctic infrastructure including research stations.

2.7 Biosecurity

This national research infrastructure area focuses on strengthening Australia's biosecurity system. It is dependent on effective research infrastructure to undertake active surveillance and diagnostics; being able to survey and rapidly diagnose, then contain and respond to threats. Strong ongoing research is critical as the potential threats, and the mechanisms required to manage them, are diverse and constantly changing. There is a need to encompass human, animal, plant and aquaculture areas.

Future Directions

Biosecurity is a risk mitigation strategy. Access to good information combined with strong implementation of good decision making processes makes it possible to act responsively and proactively to threats. The benefits of biosecurity should outweigh the costs. A world-leading biosecurity regime can improve market access opportunities. It can also play an important role in enabling the sustainable aquaculture and agriculture expansion and intensification required to realise the growth opportunities that exist for these sectors. As food safety and security becomes a growing concern around the world, we may see future opportunities to export our biosecurity related services and knowledge.

A coordinated approach of our biosecurity capability linking government, industry, researchers and the general community will best take advantage of opportunities and better manage risks.

What we have

In the past, Australia's relative isolation helped to limit biosecurity threats. Today our interconnected world makes our nation more vulnerable to the spread of pests and diseases. A strategic plan to consider geographic placement of new or upgraded facilities has strong support. It is in the national interest for regional areas to gain further capacity for innovation. High-quality fit-for-purpose research infrastructure can enable sustainable development of biosecurity research from national to regional areas.

Regional expansion in Australia creates new opportunities but has the potential to introduce new biosecurity threats (some that we may not fully appreciate) through developing pathways or hosts for pests and diseases. Biosecurity considerations are therefore important in facilitating sustainable agricultural expansion.

Australia's proximity to our northern neighbours increases the risk that pests will naturally, or with human assistance, move into mainland Australia. There is also a risk of endemic pests moving from native plants to closely related agricultural plants. To illustrate the potential impact of these types of events consider the Queensland Fruit Fly. It is a native fly originally endemic to rainforests in northern New South Wales (NSW) and Queensland. By placing agricultural crops in its native habitat it has spread to these crops and is now the single largest threat to host crop production and a major limiting factor for Australian horticultural exports.

The recent introduction of the *Biosecurity Act 2015* presents a modern approach to support Australia's biosecurity system into the future and accommodates advances in transport and technology. New national research infrastructure will align with this legislation and support its intent. The Australian Medical Research Advisory Board (AMRAB) has recommended to the

Minister for Health the importance of enhancing and coordinating research on national surveillance around emerging infectious diseases.

The Industry Growth Centres Initiative key objective is to increase collaboration between industry and research, and improve commercialisation outcomes. The Food and Agribusiness Growth Centre identified Industry Knowledge Priorities in its Sector Competitiveness Plan. The Industry Knowledge Priorities highlight what the Food and Agribusiness industry requires from the Australian research sector. Four priority areas identified are food security and sustainability, enhanced production and value addition, a global market place and the future consumer.

Research on biosecurity aspects of animal and plant health is also supported by a number of Cooperative Research Centres and various academic and private sector research institutions. These Centres have been established to strengthen scientific capacity in priority areas including plant biosecurity and invasive animal species.

Exotic Animal Diseases and High Risk Zoonoses Biosecurity

The Australian Animal Health Laboratory (AAHL) currently provides capability and capacity to research into exotic livestock disease and high risk zoonotic diseases. AAHL must be able to handle infected livestock at Biosafety Level 4 (BSL4) standards. It houses an insectary where a variety of vector-borne diseases affecting humans and animals can be contained and studied.

Major threats of pests and diseases are constant to Australia. In recent times there has been the potential for spread of Zika virus in northern Australia as the vector mosquitoes are well established in the area and already responsible for the transmission of dengue fever within Australia. Multi-drug resistant tuberculosis is endemic in Papua New Guinea, within easy reach of Australia’s Torres Strait island communities, resulting in a number of fatalities from multi-drug resistant tuberculosis cases occuring at Cairns Base Hospital, at extremely high cost to our health-care system.

Plant Biosecurity

Plant disease biosecurity is covered in a distributed network of jurisdictional, industry and university facilities. In general, coordination between facilities is not strong and support for improved connectivity is urgently needed. There is a lack of specialist scientists with skills in taxonomy, plant pathology and epidemiology. State and institutional joint ventures are aiming to address shortages. In Victoria there is a state of the art facility, AgriBio, bringing university and state based research together to create the largest agricultural R&D organisation in Victoria to address agricultural bioscience research and development in food security.

Future research infrastructure for the plant biosecurity sector should consider the National Plant Biosecurity Strategy (NPBS), a document endorsed by all governments and key plant industries.

Aquaculture and Fisheries Biosecurity

As an island nation, marine biosecurity is a significant issue for Australia. Marine biosecurity issues include marine pests and invasive species that have both environmental impact and economic impact on marine industries including ports and shipping.

Endemic aquaculture and fisheries disease research is conducted by state and territory jurisdictions and universities but there is a need for improved coordination and connectivity between the facilities. AAHL has a limited capacity to carry out work on exotic and emerging pathogens in this sector and there is a shortage of skilled scientists in this area. It is clear that development of aquaculture for warm waters must be located in the north of Australia. Developing this research could provide substantial value for the national interest. For example, northern Australian institutions and businesses could provide the research base and innovation to underpin industry development in Australia and Asia through advances in growing aquaculture-based protein production in a sustainable way. There is value in investing in cold-water aquaculture in southern Australia and warm-water in northern Australia.

What we need

Review of National Biosecurity Capability

The national approach designed to address biosecurity concerns requires research to be undertaken in the geographic location best suited to deliver results. Ideally, strategies for the containment and response to threats should be available at the closest point of incursion. To prepare Australia adequately in the long term a stocktake of current and future national facilities needs to take place. Critical mass of skilled staff and where they are located is also a major consideration.

The loss of biosecurity specific researchers through retirement without a source of qualified replacements is a national concern and needs attention. This is accentuated by a decline of young people entering the field. The recruitment of world-class scientists with strong research track records is required if we are to maintain a world leadership position and appropriately manage Australia's burgeoning biosecurity risks.

National Network for Biosecurity

A pilot that delivers a robust network for national biosecurity linking infrastructure and expertise and using information and communications technology with national coverage, is vital to the establishment of an integrated biosecurity capability for Australia. In time this could be linked internationally to take advantage of global research.

Australia already takes advantage of international and global research infrastructure for exotic diseases through collaborative research. Maintaining our local capacity in biosecurity is vital as we should not be reliant solely on overseas research. Australia must be able to diagnose and control exotic animal, plant or aquatic animal diseases or high risk zoonoses incursions, ensuring timeliness of testing and development of vaccines appropriate to Australian conditions.

Much of the investment in biosecurity has been a feature of the national priorities at the time investments were made. It is timely to reflect on the national research infrastructure to address contemporary needs.

A key requirement is a generational shift in technology resources and interconnectivity of all facilities involved in biosecurity including the establishment of a virtual laboratory network to enable sharing of large data (including digitised collections) and improved real time communication.

To ensure ongoing biosecurity research capacity there is a need to increase capability in veterinary, aquaculture and plant virology and bacteriology, veterinary parasitology and plant nematology, epidemiology and aquaculture and plant pathology. The establishment of a virtual laboratory network will allow sharing of capabilities and reduce the need for individual institutions to be capable in every field.

Plant and Aquaculture Facilities

The lack of specialised containment laboratories and greenhouses for exotic plant disease research is a serious deficiency. The existing plant facilities require collaborative networks for data sharing and connectivity to allow better coordination of work.

More extensive secure containment laboratory facilities are required for aquatic and fisheries exotic disease and emerging pathogens. While there are existing facilities for endemic disease research in various states and territories' jurisdictions and universities, there is limited national coordination. Interconnectivity and data sharing between facilities is required and will need to be supported by national collaborative networks.

National Laboratory Requirements

A networked approach can build on existing national, state and territory facilities. Laboratories within the network may specialise in different focus areas such as the development of reliable rapid diagnostic agents for particular diseases. The network will aim to strengthen synergies and improve efficiencies. A review of existing laboratory infrastructure and distributed containment facilities, including their geographic spread and level of accessibility, is required in order to determine whether the nation's current mix of facilities is optimal.

Table 9: Priority Areas for National Research Infrastructure - Biosecurity

Elements	NRI Response
National network for containment and prevention of endemic and exotic human and animal diseases	Enhance capability in animal biosecurity to enable world's best practice, including AAHL.
National network for the containment and prevention of endemic and exotic aquaculture diseases	Enhance capability in aquaculture research into exotic pathogens.
National network for the containment and prevention of endemic and exotic plant diseases	Explore integration of plant biosecurity infrastructure.
Network the national, state and territory biosecurity testing facilities	Enhance the capability and network of existing biosecurity testing facilities, including virtual laboratories and research communities.

2.8 Complex Biology

This national research infrastructure area focuses on the capacity for analysis of human, animal and plant systems to underpin new health and medical, agricultural and environmental discoveries of importance for societal, industry and policy applications. The field of study in biology known as omics involves the measurement and characterisation of large numbers of biological molecules, typically genes (genomics), proteins (proteomics), lipids (lipidomics) or metabolites (metabolomics) from individuals or populations. Omics then investigates how the pools of biological molecules identified translate into the structure, function, and dynamics of organisms.

Future Directions

Over the next ten years, we will see continued dramatic expansion in the availability of biologics-based therapeutic agents targeting specific diseases and tumours. These therapies will be designed to meet individual needs. This will be achieved by advances in omics, which have revolutionised biology in the past decade, by efficient clinical trials, and by data linkage, modelling and visualisation capabilities.

In the immediate future genomics, proteomics, metabolomics and molecular diagnostic technologies will lead to medical discoveries that will underpin the health, wellbeing and prosperity that enhance Australia's social and economic wealth.

The biological sciences will also make a significant impact on our ability to manage and sustain essential environmental ecosystems and improve agricultural productivity. In order to increase agricultural production sustainably, we must combine the best performing plant varieties with best farming practices, both adapted to the local environment. Advances in plant science are essential to meet these goals.

What we have

Coordinated Research Network

Global research advances across medicine, agriculture and environment are critically dependent on biomolecular research. Australia has a robust national research infrastructure across the four major technology platforms – genomics, proteomics, metabolomics and bioinformatics provided by BPA. These services are offered through 18 separate facilities around the country. Their focus spans biomedicine, bio-industry, agriculture and the environment.

Multiple data sets generated by BPA coupled with metadata from the IMOS are enabling new collaborative research insights into marine microbes. BPA has also instigated a number of national collaborative research efforts that bring together experts in all areas of marine microbiology.

Plant Phenomics

Plant phenomics will play an important role in addressing the most pressing global food security issues over the next decade. These include food production and food quality, sustainable agriculture, alternative fuels, materials and chemicals, and global climate change. APPF provides world-class capability to carry out high throughput phenotyping of crops and model plants, linking genomics and phenomics to help address research priorities.

Biobanking

Most biobanks comprise tissue samples collected by clinicians in their speciality, such as cancers, which utilise omics and patient samples to uncover the genetic basis of disease. Australia has a range of high-quality biobanks that are immensely valuable to biomedical research, but are not currently coordinated.

Synthetic Biology

Synthetic biology is a potentially disruptive technology transforming the scope and scale of biological systems engineering, in which living cells are used as complex, self-replicating catalysts to perform long series reactions under inherently safe conditions in simple reactor systems. Low carbon footprint biotechnology processes, where specialised cells have been constructed using synthetic biology are gradually replacing classical organic chemistry for the production of everything from fuels and bulk chemicals to fine chemicals and pharmaceuticals. Already more than 50 per cent of new drugs are biopharmaceuticals.

Australia has the potential to become a significant specialist biotechnology manufacturer.

Potential areas of impact include:

- drug development and genome engineering in both medical sciences and agriculture,
- novel monitoring methods in environment and natural resource management, and
- high-throughput automated strain development to develop novel bioprocesses producing a range of bio-derived existing and novel chemical compounds.

This emerging field challenges conventional molecular biology methods by using large scale DNA synthesis and assembly infrastructure to produce and modify synthetic genomes and organisms. Synthetic biology offers the potential for new molecule development including antibodies, vaccines, pharmaceuticals and antimicrobial agents as demonstrated in the Tasmanian devil case study later in this section.

This capability sits at the intersection of omics, bioinformatics, bioengineering and biochemistry and will play an increasingly important role in a diverse portfolio of research.

What we need

Coordinated Research

Much complex biology is dependent on state-of-the-art omics research infrastructure, and it will be essential that this research infrastructure is maintained and developed as new techniques and methodologies are developed.

Similar to other focus areas there are critical generic and domain specific eResearch needs to enable the collection and analysis of large amounts of data produced by mapping the genomes of humans, tissue specimens, relevant animals and micro-organisms. Coupled with the necessary bioinformatics capabilities for analysis, data can be translated into research outcomes, including agricultural innovation or policy decisions for communities, industries and government.

There are efficiencies of scale and increased opportunities for interdisciplinary research if related life sciences facilities are grouped or networked. Integration of environmental biobanks and monitoring systems will allow Australia to continue as a world leader in environmental genetics. A significant challenge will be to improve our understanding of how microbes perform the critical functions that sustain the viability, resilience and health of our marine ecosystems and their impact on soil health.

A national, holistic approach to tissue and specimen banking, such as omics and seed, for research across the environment, agriculture, forestry and biosecurity will become a fundamental need as environmental omics and microbiology grow in importance for environmental research. This will play a critical role in improving biodiversity, agricultural yields and adaptation to climate change.

Plant Phenomics

New national investments in plant biology research must span from the cell to the field or farm and must support research aligned both physically and strategically to Australia's agricultural production and food industries. A coordinated national approach to next generation plant phenotyping infrastructure will ensure optimal integration with molecular phenotyping and whole-of-plant phenomics, to provide food and biosecurity and underpin Australia's agricultural exports. A commensurate investment in next-generation bioinformatics and computing for image analysis, genome-scale breeding, bionetwork interrogation and predictive model development will be needed for Australia to build upon existing NCRIS capabilities.

Biobanking

Biobanks are enablers across a range of medical, agricultural and biodiversity research. Integrating existing tissue and environmental biobanks into collaborative networks linked to the research community, ensuring the ability to collect, store and analyse high quality useful research data will provide significant improvement in research effectiveness.

Linking established biobanks into a national network of central tissue repositories will turn an under-utilised product into a more valuable research resource. Under a national system for collecting and biobanking human tissue samples, standards for data gathering and sample curation would assist in the sharing of materials and would foster collaborations. Inclusion of genomics, proteomics and metabolomics data with health, lifestyle and clinical data, will magnify our ability to develop new therapies.

While the necessary institutional processes are in place in the network of natural history museums, herbaria and seedbanks, medical biobanking is fragmented. Australia would also benefit from a population biobank. A population biobank has unique value for population genomics and research into the causes, prevention and treatment of disease. Other countries have well established population biobanks that provide infrastructure for public health research. We should explore existing networks and capabilities, for example through a pilot building on an existing network, to move towards a national biobank network.

Synthetic Biology

Synthetic biology is dependent on access to high level omics capabilities and the associated bioinformatics and systems biology skills. The need to maintain this research infrastructure in Australia has already been addressed.

There are demonstrated world-class capabilities in Australia to design, test and refine bacterial strains using synthetic biology for industrial partners. Globally there are groups developing large scale automation of their strain development programs, where from a computer terminal researchers design assemble and characterise up to 1000 different strains per week. It is proposed that in the first instance, Australia should gain access to such facilities by way of collaboration.

Australia has a recognised tradition of strength in agricultural research. We have an industry with scientific and technological advantages providing a competitive advantage in this part of the world. Bio-based production is viable at a smaller scale than traditional petrochemical plants, and raw material costs dominate production costs. The location of plants close to low cost raw materials is essential. Australia provides low cost sugar cane and sorghum starch and so is ideally suited, given the proximity to Asian markets, to develop new industries driven by synthetic biology

These applications depend on the design-build-test iterative process of synthetic biology technologies, most effective when automated, high-throughput technological platforms are accessible. These platforms help ensure the quality of the research and eventual products by providing high-quality, standardised materials for research.

Large Animal Genome Engineering

Large animal genome engineering could complement Australia's existing small animal (mouse) phenomics capability, and availability of other biosecurity and biomedical facilities. The ability to genetically modify the mouse genome has revolutionised biomedical research resulting in numerous scientific breakthroughs and commercial developments. The advent of CRISPR-Cas9 technology now means that these similar opportunities exist for livestock species that are widely used in biomedical research, including gene discovery, the development of large animal disease models, commercial applications including growing organs for xenotransplantation, antibody production and drug development.

Case Study - Creation of new devices, instruments and therapeutics

Synergies between discoveries may enable creation of new devices, instruments and therapeutics. Researchers from Sydney and Hobart recently published a paper that could have significant impact as clinicians wrestle with the global rise of microbial resistance to antibiotics. The initial question was why Tasmanian devil joeys - born without an adaptive immune system - survive in a pathogen-laden pouch and burrow. Using a range of technologies and international collaboration on genomics, peptide and protein chemistry, structural biology and bioinformatics, the team identified a number of antimicrobial peptides secreted in the dam's pouch lining and milk. Two of the peptides called cathelicidins have been shown to have broad spectrum antibacterial capability against the important human pathogens Methicillin-resistant Staphylococcus aureus (MRSA) and Vancomycin-resistant Enterococcus faecalis (VREF). A third cathelicidin is active against fungi, which also has ramifications in health care.

Some of this research was carried out using existing BPA infrastructure, an example of the importance and unexpected benefits of investments in national research infrastructure.

Large animal models of human disease have great potential to contribute to the major fields of medical research such as cardiology, oncology and neurodegenerative disease, as well as agricultural research. Pigs and sheep are widely used in biomedical research and modelling, because of similarities with humans in organ size, anatomy, physiology, metabolism and genetics including cardiovascular and neurodegenerative diseases. The ability to genetically modify these animals provides possibilities to explore the mechanistic basis of disease such as Alzheimer's disease, develop new therapies and engineer organs suitable for transplantation.

This type of capability would naturally collaborate with existing facilities such as the AAHL.

Table 10: Priority Areas for National Research Infrastructure - Complex Biology

Element	NRI Response
Network to drive translation of omics data	Enhance existing BPA capability in proteomics and metabolomics to enhance the collection, storage and analysis of genome data coupled with bioinformatics capabilities in medical, agricultural and environmental research.
Plant phenomics	Enhance current APPF capability and support a national approach to next generation plant phenotyping, including bioinformatics support.
Networked biobanks	Explore opportunities to establish a national network to coordinate and enhance current biobank capability.
Software engineering, bioinformatics and automation	Explore establishing Australia's national capability in synthetic biology through leadership standardisation, biologics production and process automation.

2.9 Therapeutic Development

This National Research Infrastructure is required to progress a concept for a therapeutic agent or medical device through discovery, low-volume production and pre-clinical investigations followed by clinical testing. The aim is to better support the development of products so they can be brought to the clinic and to commercial reality.

Future Directions

More effective therapies will come from new insights into the molecular structure of biological macromolecules, especially proteins and nucleic acids, how they acquire their structures, and how structural alterations affect their function. These developments will enhance Australia's participation in the global endeavour of personalised medicine.

The ability to better transform data into medically useful insights will be a standout difference in ten years' time. We will have a more skilled research workforce, able to integrate and interpret data across an array of platforms, and this will create new opportunities in health protection, and in solving complex health and social problems, including in indigenous health.

What we have

The product development flow for a new medical therapy or device has three main aspects:

1. discovery of potential product candidates which may involve biobanks and high-throughput screening
2. production of candidate molecules at appropriate quality and scale, and
3. testing the candidates in preclinical animal models and well-designed clinical trials.

While some of these elements exist in Australia, there are significant gaps in capability and coordination. The process of research translation of novel molecular candidates into social and economic outcomes must be a current and future national priority.

Australia has demonstrated competiveness and the beginnings of a critical mass in some areas of therapeutic development.

The newly established MRFF and the BTF will provide a significant boost to health and medical research in Australia. They will also create increased demand for existing national research infrastructure that is already fully utilised in a number of areas. Coordinating the planning of research infrastructure must strengthen or modify the existing national research infrastructure so as to meet these increased demands.

Discovery

Novel drug candidates may be small molecules derived from chemical synthesis or larger protein molecules produced from recombinant biotechnology. Both these types of candidates may be discovered in libraries by screening and selection using sophisticated high throughput assay systems.

An example of small molecule screening infrastructure is Compounds Australia. It provides compound management research logistics, lodgement and storage, specialised formatting and reformatting into assay-ready microplates, quality control, data handling to a range of universities, medical research institutes, biomedical companies and international member organisations. Recent adjuncts to high throughput screening are fragment screening and high content imaging (HCI). These and other techniques including NMR spectroscopy, Surface Plasmon Resonance (SPR) and X-ray crystallography, enhance the ability to evaluate rapidly the biological potential of many hundreds of thousands of molecules and compounds and enable more efficient progression of potential lead molecules.

There is rapidly growing demand for libraries of molecules, antibodies, bi-specific antibodies and antibody fragments to be used in screening for use in immunotherapy and for the targeted delivery of nanoparticles carrying therapeutic agents.

The development of large molecule protein therapeutics has resulted in an explosion of new licensed biotech products over the last 25 years. Discoveries continue to be made using protein, cell, RNA interference (RNAi) and gene therapies, and gene editing that may improve human health and wellbeing. These capabilities are reflected in a number of the current NCRIS investments, such as BPA and the Australian Phenomics Network (APN).

Australia would benefit from establishing large scale, high quality animal breeding and genome engineering facilities. This is addressed more fully in the Complex Biology section. To be productive, these would need to be coupled with high-throughput assay screening to facilitate therapeutic target identification. Part of the necessary capability would be scientists trained in medicinal chemistry, bioengineering and bioinformatics.

Production

Translation of novel molecules or cells into therapeutic candidates requires sophisticated and specific production facilities. Biologics are now the most rapidly growing class of new therapeutics, accounting for six of the world's ten top selling human drugs.

Case Study - National Biologics Facility (NBF)

The NBF at the University of Queensland was established in 2007 to assist Australian biotechnology companies and academic researchers bridge the gap between laboratory experiments and the well-characterised cell lines and bioprocesses required to produce material suitable for pre-clinical and clinical use. NBF's partnerships with leading global biologics companies and researchers illustrates of the role that Australia can play in developing novel biologics of global interest. For example, in 2011 the Queensland Government approached NBF for help with an outbreak of the lethal Hendra virus in that state. Using a monoclonal antibody sourced from the USA, NBF quickly developed a bioprocess to make antibody material suitable for urgent compassionate use in patients. Since then a Phase 1 clinical trial has successfully been run in Brisbane – a first step along the usual path for approval for new therapies.

Testing

A crucial step in translating novel molecular candidates into patient and economic benefit is through pre-clinical testing and properly conducted clinical trials. The Australian New Zealand Clinical Trials Registry (ANZCTR) is the national registry, and an integral part of the World Health Organisation's International Clinical Trials Registry Platform (WHO ICTRP).

This registry gives industry, clinicians, researchers and patients or consumers access to high quality information on clinical trials being conducted in Australia including Australian recruitment site locations.

What we need

Australia is well positioned to build on investments in certain areas of medical research. The 2016 Roadmap consultations provided clear messages around translating therapeutic developments. Australia needs:

- facilities for discovery that enable high throughput screening for identifying both small and large molecule candidate therapeutics
- production facilities to make appropriate quality candidates for pre-clinical and clinical testing
- the ability to design, mount and execute high quality, ethical clinical trials to test product candidates
- translation of evidence to practice through clinical trials infrastructure, including linked trials data, health service research infrastructure and infrastructure that allows tapping into available data sets
- human capital for supporting the discovery, production and testing of novel therapeutic candidates
- linking health and disease control agencies' data sets with researchers and reference laboratories, and
- a national framework for biobanks in Australia connected seamlessly to informatics infrastructure.

Discovery

National compound management facilitates the work of individual Australian health and medical research organisations by avoiding duplication and centralising the integration, maintenance and operation of highly specialised and highly sophisticated infrastructure. While Australia has many molecule libraries held by companies and made available to researchers, we would benefit greatly from an integrated compound management and drug discovery capability.

Australia is unlikely to be able to encompass all the technical screening discovery pathways described earlier. As it is not cost-effective for all research institutions to have this technology in situ, outsourcing fragment screening to a leading facility, will have the advantage of improving cost-effectiveness by minimising unnecessary duplication of high-end infrastructure such as Fourier transform mass spectrometers and NMRs.

Growing the existing partial solution that we have now should be a national priority, to enable the process of research translation of novel molecular candidates into social and economic benefits.

Production

National production facilities for making candidate biological molecules of the appropriate pre-clinical and GMP clinical-grade quality will facilitate research translation and therapeutic development in Australia. Most of these candidates are likely to be recombinant proteins in the next ten years. Gene and cell therapies are also important areas of growing potential medical research.

Testing

Appropriately produced candidate therapeutics requires pre-clinical and clinical testing. Research infrastructure that provides sophisticated animal model product testing to support high quality Australian-based clinical trials, will be essential to keeping the medical research translation process in Australia so that we can reap economic and societal benefits.

Research infrastructure that supports translation of discoveries into clinical application by facilitating high quality clinical trials is critical. A nationwide research infrastructure with networked co-ordinating centres that support trials and clinical quality registries is essential for delivering improved health outcomes.

Our testing capability will be improved though a national clinical trials registry with a data repository function, which will ensure researchers can lodge and control their own data.

The increasing need for clinical research transparency and accountability requires a streamlined, secure system of data sharing between clinical trial registries. This must extend to interoperability with other entities such as state-based Human Research Ethics Committees, using the new national Human Research Ethics Application form and collaboration with national regulatory bodies such as the TGA.

Integration

Using securely linked health data sets such as MBS, PBS, disease and surgical registries, clinical and administrative data and broader government data such as social determinants of health, will advance Australia's capacity for more effective service design, public health interventions and policies. This could be achieved through expanding data linkage platforms, for example PHRN, to enable real-time clinical, biobanking and genomic data integration.

This capability must be underpinned by eResearch systems and skilled analysts to provide timely recognition of disease outbreaks and identify pathogens of public health concern.

Australia should build soft infrastructure in the health care system so that every patient admission is viewed as a research event. De-identified data from all patient admissions should ideally be available for research and policy making.

Table 11: Priority Areas for National Research Infrastructure - Therapeutic Development

Element	NRI Response
High throughput methods for candidate discovery, manufacturing and testing	Enhance capability to coordinate discovery activities and enhance the existing national candidate (both small and large molecule) management capability. BPA is currently contributing to this capability on a national level.
Bioengineering solutions for next-generation products and devices	Explore integration of facilities into a harmonised network that make quality materials – recombinant proteins for the research sector, cell based therapies and stem cell core facilities, for scalable therapeutic development and manufacture. Current capability through NCRIS: BPA and APN.
Advanced health research translation	Explore establishing new, or enhancing existing networks focused on pre-clinical testing, sophisticated animal testing, clinical trials and data linkage.
Integration of existing and emerging large-scale population, tissue, microbial and genomics datasets	Explore integration of existing institutional and jurisdictional level capabilities across a range of data platforms, through a small number of 'trusted data custodians' enabling greater researcher access to appropriate existing data sets. All elements require a focus on human capital; people trained in medicinal chemistry, biological sciences, bioengineering and bioinformatics. BPA (in both health, agricultural and environmental domains) and PHRN in health.

3 Prioritised National Research Infrastructure

3.1 Prioritised National Research Infrastructure

The successful implementation of the 2016 Roadmap will require consideration of the following research infrastructure focus areas and their respective elements. A summary of the key elements, demonstrating the breadth of activity that will be considered in the development of the National Research Infrastructure Investment Plan is set out in the following table.

Table 12: Prioritised National Research Infrastructure

Focus Areas	Elements
Digital Data and eResearch Platforms	Tier 1 HPC
	Create national research data cloud
	Research networks
	Access and authentication
Platforms for HASS	Integrated and coordinated HASS platform
	Harmonised platforms for Indigenous research
	Harmonised platforms for social sciences research
Characterisation	National network of microscopy and microanalysis
	National network of biomedical imaging
	Neutron scattering, deuteration, beam instrumentation, imaging and isotope production
	Synchrotron capabilities
	Accelerators for imaging
Advanced Fabrication and Manufacturing	Fabrication of materials and devices on a micro or nanoscale
	Bioengineering and bio fabrication
	Engineering capability for new classes of fabricated devices
Astronomy and Advanced Physics	Astronomy infrastructure
	International accelerator programs and instruments
	Precision measurement
	National nuclear facilities
Environmental Systems	Environmental prediction system
	Inward focused Earth monitoring and exploration
	Remotely sensed Earth observations
	Agricultural integrated networks
	Marine systems
Biosecurity	National network for containment and prevention of endemic and exotic human and animal diseases
	National network for the containment and prevention of endemic and exotic aquaculture diseases
	National network for the containment and prevention of endemic and exotic plant diseases
	Network the national, state and territory biosecurity testing facilities
Complex Biology	Network to drive translation of omics data
	Plant phenomics
	Networked biobanks
	Software engineering, bioinformatics and automation
Therapeutic Development	High throughput methods for candidate discovery, manufacturing and testing
	Bioengineering solutions for next-generation products and devices
	Advanced health research translation
	Integration of existing and emerging large-scale population, tissue, microbial and genomics datasets

3.2 Implementing the Roadmap

The successful implementation of the 2016 Roadmap will require a staged approach. Over the decade of implementation there will be points of review and realignment to respond to emerging priorities and new opportunities. Governance arrangements outlined in Chapter 1 should be addressed as the first step, as ongoing and continuous oversight will play an important role in implementation.

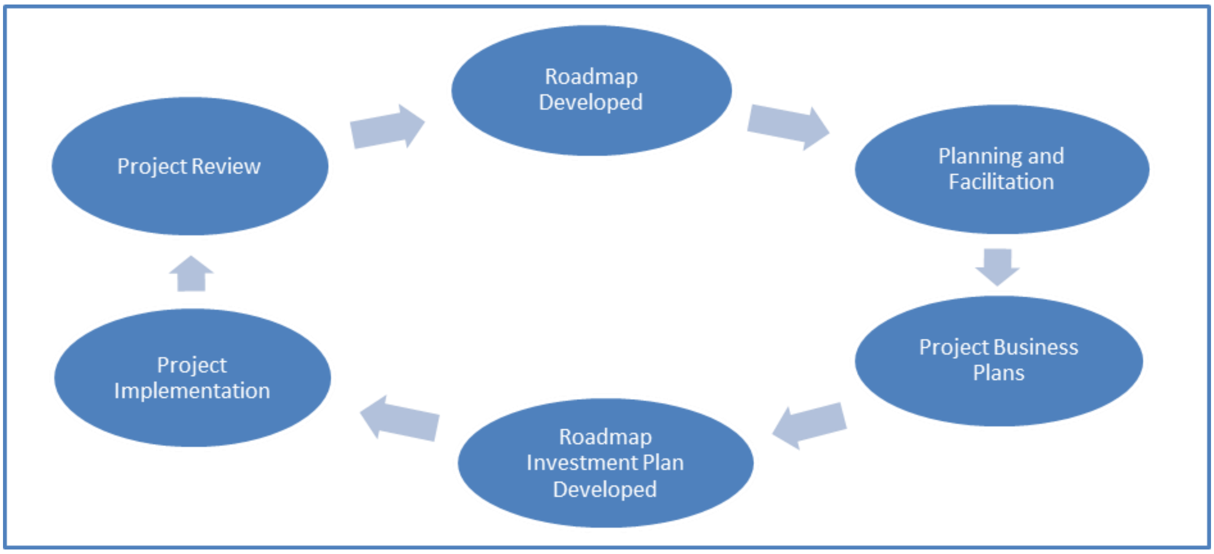
To address the range of research infrastructure requirements identified in the 2016 Roadmap, a whole of system approach addressing national interest, benefit and impact is required. A coordinated portfolio of investments in research infrastructure must consider support for a range of potential facilities and projects of varying sizes to meet national needs.

Roadmap Investment Plan

Once the governance arrangements are in place an Investment Plan must be developed to optimise the available resources into a strategic whole of government response to the Roadmap. To inform the Investment Plan, individual focus area strategy plans must be developed addressing the research infrastructure requirements identified in the Roadmap.

A successful model previously employed to develop the NCRIS network relied on independent and highly respected facilitators to engage with key stakeholders to develop strategic responses to individual focus area requirements through a consultative facilitation process. It is recommended that this approach be used in the future to inform a whole of government Investment Plan for Government consideration.

Figure 2: National Research Infrastructure Planning Process



Planning and Facilitation

Facilitation within focus areas will engage relevant stakeholders to identify needs at a practical and technical level. The purpose will be to prioritise current and future funding requirements based on issues identified in the 2016 Roadmap. The move towards a more integrated research infrastructure system means that the facilitation process may need to consider a number of capability areas in parallel.

In moving from focus 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. Depending on the identified need, this will involve examining existing capability at the facility or project level, identifying gaps where new activity is required or redesigning or terminating existing activity.

Development of project business plans will flow from the facilitation process and set out how the research infrastructure needs will be delivered. Implementation plans will be whole of life cycle and include facility or project structure, funding including indicative co-investment, project collaborators and governance arrangements.

The project business plans must be developed in the context of the National Research Infrastructure Principles outlined in section 1.3 and will provide the vehicle for engagement with key stakeholder and co-investors.

Project Implementation

Implementation of agreed project business plans will be governed by formal project contracts that will be commissioned once the funding is available.

Project implementation can take one of three forms:

- **Pilot** – a small scale test project for nascent or emerging national research infrastructure areas. Funding would be provided for a period sufficient to test the proposal and should not run for longer than five years.
- **Establishment** – a project is established from either greenfield or a pilot project with an agreed level of funding and timeframe determined by the type of research infrastructure.
- **Continuing** – an ongoing activity may be enhanced, downscaled or kept at its current level with funding in line with the Implementation Plan.

At appropriate times facilities or projects will come to end of life or will no longer be a priority for national research infrastructure investment. Once identified, these projects should be transitioned appropriately, which may involve decommissioning or transfer to an institutional arrangement.

Project Review

Life cycles for national research infrastructure vary significantly depending on technology, advances in methods and processes, and the rapidly changing requirements of leading edge research. It is imperative that all facilities and projects in the national research infrastructure system are regularly reviewed for efficiency and effectiveness prior to a new Roadmap being developed. Reviews will look at two main elements of the project – governance and management performance, and national impact. Reviews will be conducted independently under the auspices of the national research infrastructure advisory group.

4 Annexes

4.1 Expert Working Group

The EWG comprises eminent Australian's from the research community, the university sector, industry and government.

- Dr Alan Finkel AO, Australia's Chief Scientist (Chairman)
- Professor Edwina Cornish AO, (Deputy Chairman), Provost and Senior Vice-President, Monash University
- Professor Aidan Byrne, Provost, University of Queensland and previous immediate Chief Executive Officer, Australian Research Council
- Dr Andrew Cuthbertson AO, Chief Scientific Officer and R&D Director, CSL Ltd
- Professor Sandra Harding, Vice Chancellor and President, James Cook University
- Mrs Rosie Hicks, Chief Executive Officer, Australian National Fabrication Facility Ltd
- Professor Anne Kelso AO, Chief Executive Officer, National Health and Medical Research Council
- Professor Suzanne Miller, Chief Executive Officer and Director, Queensland Museum
- Dr Adrian (Adi) Paterson, Chief Executive Officer, Australian Nuclear Science and Technology Organisation (ANSTO)
- Professor Andy Pitman, Director, ARC Centre of Excellence for Climate System Science

4.2 Taskforce

The Expert Working Group was supported by a Taskforce. The whole-of-government Taskforce is based in the Department of Education and Training and includes experts from the Department of Industry Innovation and Science, the Department of the Environment and Energy, and the Department of Health. The members of the Taskforce are:

Ms Ditta Zizi (Taskforce Head), Mr Ryan Winn, Ms Dani Farrow, Mr Nicolas Carrin, Dr Geraldine Cusack, Mr Lee Harris, Mr Andrew Munro, Mr Tim Wotton, Mr Kevin Tang, Mr Luke Atchison, Mr Hugh Ross, Ms Laura Rohan-Jones, Ms Margaret O'Connor, Ms Anna Mayberry, Ms Sandi Den Hertog, Ms Sharon Hewett.

4.3 Capability Issues Paper and Related Consultation Process

The National Research Infrastructure Capability Issues Paper (Issues Paper) was released on 20 July 2016 to support consultation around development of the 2016 National Research Infrastructure Roadmap. It presented a range of issues relating to national research infrastructure capability areas and was the first step in working towards a shared view of the capabilities needed to support current, new and emerging areas of research and innovation.

The Issues Paper was developed with the assistance of invited capability experts who worked diligently and with great expertise to help define the capabilities and focus areas, and to consult widely with other leading Australian and international experts. They were:

- Em Prof Mary Barton, School of Pharmacy and Medical Sciences, University of South Australia
- Dr Helen Cleugh, Science Director, Oceans and Atmosphere Flagship, CSIRO
- Mr Alec Coles OBE, CEO, Western Australian Museum
- Dr Jackie Craig, Chief, Cyber and Electronic Warfare Division, Defence Science and Technology Group
- Dr Joanne Daly, Fellow, National Research Collections and Informatics, CSIRO
- Mr John Gunn, CEO, Australian Institute of Marine Science
- Prof Mark Hutchinson, Director, Centre for Nanoscale Biophotonics, University of Adelaide
- Dr Cathy Foley, Chief, Division of Materials Science and Engineering, CSIRO
- A/Prof Peter Gibbs, Laboratory Head, Systems Biology and Personalised Medicine, Walter and Eliza Hall Institute of Medical Research
- Prof Peter Gray, Research Leader, Mammalian Cell Lines and Stem Cell Bioprocesses, University of Queensland
- Ms Cathrine Harboe-Ree, University Librarian, Monash University
- Prof Sunil Lakhani, Head, Academic Discipline of Molecular and Cellular Pathology, University of Queensland
- Dr David Mitchell, CEO, Australian Centre for Plant Functional Genomics
- Prof Robyn Owens, Deputy Vice-Chancellor (Research), University of Western Australia
- Prof Bob Pressey, Chief Investigator, ARC Centre for Excellence for Coral Reef Studies, James Cook University
- Prof Matthew Sanders, Director, Parenting and Family Support Centre, University of Queensland
- Prof Timothy Senden, School Director, Research School of Physics and Engineering, Australian National University
- Prof Sally Redman AO, Chief Executive Officer, Sax Institute
- Prof Lynette Russell, Director, Monash Indigenous Centre, Monash University

Immediately following the release of the Issues Paper, Expert Working Group and Taskforce members undertook an intensive seven week Australia-wide program of research infrastructure facility visits in conjunction with extensive stakeholder consultations in Perth, Adelaide, Brisbane, Townsville, Canberra, Sydney, Hobart and Melbourne.

Over 580 people registered their attendance at 36 consultation sessions. The EWG visited 51 facilities and received 325 written submissions in response to the Issues Paper.

A copy of the Issues Paper and the publicly available written submissions can be found on the Department of Education and Training's website at: www.education.gov.au/consultations-national-research-infrastructure-capability-issues-paper

4.4 Terms of Reference - 2016 National Research Infrastructure Roadmap

The 2016 National Research Infrastructure Roadmap (2016 Roadmap) is an initiative under the Australian Government's NISA announced by the Prime Minister, the Hon Malcolm Turnbull MP, on 7 December 2015.

The 2016 Roadmap will set out Australia's long term research infrastructure needs and propose future areas of investment so that Australia continues to maintain its research excellence and increases innovation across the economy to the benefit of the nation.

The 2016 Roadmap, led by Australia's Chief Scientist, has been established to provide advice to the Australian Government through the Ministers for Education and Training and Industry, Innovation and Science on future priorities for strategic investment in those key national research infrastructure capabilities that would support and develop Australia's research capacity and underpin research and innovation outcomes over the next five to ten years.

The Chief Scientist will be assisted by an EWG in the development of the new 2016 Roadmap.

The 2016 Roadmap will develop a prioritised plan for the coming decade for investment in national research infrastructure capability that will advance science and research for a healthy, sustainable and prosperous Australia and position the nation to respond to the world's big research challenges.

Accordingly, the 2016 Roadmap will:

- identify Australia's national research infrastructure needs to underpin future research and innovation capability
- consider where Australia already has world-class research infrastructure capability and identify existing and emerging areas for future strategic development or prioritised investment
- determine areas where capacity building of the national research infrastructure system or decommissioning of existing capacity will be of strategic benefit to Australia's research effort
- identify those international trends and best practices that will determine whether Australia's national research infrastructure investment can be world-class and provide international leadership
- identify how Australia's national research infrastructure investment can be aligned to Australia's National Science and Research Priorities and other Government priorities such as NISA, so as to increase collaboration within the research system both nationally and internationally and with the users of research such as business and industry
- identify opportunities for partnerships and co-investment with key stakeholders in the research sector, particularly industry and other end users of research, that will leverage the Government's investment in national research infrastructure
- provide guidance on where Australia can take advantage of international or global research infrastructure and build regional sharing arrangements, and
- provide guidance to the Government on priorities and possible allocation of operating funding under NCRIS.

In developing the 2016 Roadmap, the Chief Scientist leading the EWG will:

- seek expert advice on research infrastructure capability and investment needs
- consult with the research community, the university sector, public and private research institutes, research funders, state and territory governments, peak organisations, existing facility operators, publicly funded research agencies, international organisations, federal government agencies and importantly users of research such as industry and business
- provide stakeholders and the community more broadly with the opportunity to provide feedback on a draft 2016 Roadmap, and
- provide regular updates on progress to the Minister for Education and Training and the Minister for Industry, Innovation and Science.

The EWG will be supported by the Department of Education and Training through a dedicated secretariat.

4.5 Acronyms

Acronym	Description
AAD	Australian Antarctic Division
AAF	Australian Access Federation
AAHL	Australian Animal Health Laboratory
AAL	Astronomy Australia Limited
AARNet	Australian Academic and Research Network
ACCESS	Australian Community Climate and Earth System Simulator
ACOLA	Australian Council of Learned Academies
AIATSIS	Australian Institute of Aboriginal and Torres Strait Islander Studies
AIMS	Australian Institute of Marine Science
ALA	Atlas of Living Australia
AMMRF	Australian Microscopy and Microanalysis Research Facility
ANDS	Australian National Data Service
ANFF	Australian National Fabrication Facility
ANSTO	Australian Nuclear Science and Technology Organisation
ANU	Australian National University
ANZCTR	Australian New Zealand Clinical Trials Registry
APN	Australian Phenomics Network
APPF	Australian Plant Phenomics Facility
ARC	Australian Research Council
AREN	Advanced Research and Education Network
ARF	Asset Recycling Fund
ASKAP	Australian Square Kilometre Array Pathfinder
ATSIDA	Aboriginal and Torres Strait Islander Data Archive
AuSREM	Australian Seismological Reference Model
AURIN	Australian Urban Research Infrastructure Network
BOM	Bureau of Meteorology
BPA	Bioplatforms Australia
BTF	Biomedical Translation Fund
BSL4	Biosafety Level 4
CALD	Culturally and Linguistically Diverse Communities
CERN	European Organization for Nuclear Research
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CRC	Cooperative Research Centre
CT	Computed Tomography
EBI	European Bioinformatics Institute
EIF	Education Investment Fund
EMBL	European Molecular Biology Laboratory
ESFRI	European Strategy Forum on Research Infrastructures
EWG	Expert Working Group
FAIR	Findable, Accessible, Interoperable and Reusable
GA	Geoscience Australia
GBI	Global Bioimaging
GBIF	Global Biodiversity Information Facility
GMP	Good Manufacturing Practice
GMT	Giant Magellan Telescope
GOOS	Global Oceans Observing System
GRACE	Gravity Recovery and Climate Experiment
HASS	Humanities, Arts and Social Sciences
HCI	High Content Imaging
HEEF	Higher Education Endowment Fund
HIA	Heavy Ion Accelerator
HPC	High Performance Computing
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IMOS	Integrated Marine Observing System

Acronym	Description
IODP	International Ocean Discovery Program
IoT	Internet of Things
ISO	International Standards Organisation
ITER	International Thermonuclear Experimental Reactor
LIEF	Linkage Infrastructure Equipment and Facilities
LIGO	Laser Interferometer Gravitational-Wave Observatory
MBS	Medicare Benefits Scheme
MNF	Marine National Facility
MNRF	Major National Research Facilities
MRFF	Medical Research Future Fund
MRI	Magnetic Resonance Imaging
MRSA	Methicillin-resistant Staphylococcus aureus
MWA	Murchinson Widefield Array
NASA	National Aeronautics and Space Administration
NBF	National Biologics Facility
NCI	National Computational Institute
NCIG	National Centre for Indigenous Genomics
NCOA	National Commission of Audit
NCRIS	National Collaborative Research Infrastructure Strategy
NDF	National Deuteration Facility
NeCTAR	National eResearch Collaboration Tools and Resources
NHMRC	National Health and Medical Research Council
NIF	National Imaging Facility
NISA	National Innovation and Science Agenda
NMI	National Measurement Institute
NMR	Nuclear Magnetic Resonance
NPBS	National Plant Biosecurity Strategy
NSRPs	National Science and Research Priorities
NREN	National Research and Education Network
NRI	National Research Infrastructure
OPAL	Open-Pool Australian Lightwater Reactor
PARADISEC	Pacific and Regional Archive for Digital Sources in Endangered Cultures
Pawsey	Pawsey Supercomputing Centre
PBS	Pharmaceutical Benefits Scheme
PET	Positron Emission Tomography
PFRA	Publicly Funded Research Agency
PHRN	Population Health Research Network
RDA	Research Data Alliance
RDS	Research Data Service
RV	Research Vessel
SKA	Square Kilometre Array
SPECT	Single-Photon Emission Computed Tomography
SPR	Surface Plasmon Resonance
SSI	Super Science Initiative
TERN	Terrestrial Ecosystem Research Network
ToR	Terms of Reference
VREF	Vancomycin-Resistant Enterococcus Faecalis
WHO ICTRP	World Health Organisation International Clinical Trials Registry Platform