Australian Academy of Science

PHYSICS DECADAL PLAN 2012–2021

BUILDING ON EXCELLENCE IN PHYSICS

UNDERPINNING AUSTRALIA'S FUTURE

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GPO Box 783, Canberra ACT 2601

The *Physics decadal plan 2012–2021: building on excellence in physics* consists of two documents:

The *Physics decadal plan 2012–2021: building on excellence in physics, underpinning Australia's future* contains a summary of the findings of the physics decadal plan process and provides the main recommendations for addressing the current issues identified within Australia's physics community. This document is the *Physics decadal plan 2012–2021*.

The *Physics decadal plan 2012–2021 research report: building on excellence in physics, underpinning Australia's future* contains the background and foreground research from which the findings presented in the *Physics decadal plan 2012–2021* have been drawn. The data in the *Physics decadal plan 2012–2021 research report* can also be used for benchmarking future changes in this field.

Both parts may be downloaded from the physics decadal plan website **www.science.org.au/natcoms/physicsdecadalplan.html**.

ISBN 978 0 85847 338 6

Cover image www.istockphoto.com/aleksandarvelasevic

Foreword

Physics lies at the heart of science, crossing the boundaries of chemistry, biology, engineering and medicine, and providing us with an increasingly quantitative view of the world around us — allowing us to design solutions to outstanding problems and invent new ideas that are revolutionising our world.

The power of physics has recently been highlighted in the reported discovery of the Higgs boson — a prediction of a theory which provides a description of three of the four fundamental interactions between elementary particles. This theory builds on centuries of work by physicists including Galileo, Newton, Maxwell, Einstein and Feynman.

But physics has done much more than provide a fundamental understanding of the world in which we live; it has also underpinned huge changes to society and our quality of life — including the industrial revolution, electricity, electronics, computers, medical imaging and aerospace technology.

The search for the Higgs boson is also a wonderful illustration of what is needed to make such great leaps in understanding — it was a collaborative effort demanding major resources. And Australia was there, playing a small but significant role as part of a huge transnational effort. This would not have happened, however, without a long-term investment in our education system, in our universities, in large research infrastructure such as the synchrotron, and in our capacity to engage internationally.

Just as an understanding of electrons and photons has led spectacularly to many of the electronic and optical products in our lives today, a deeper understanding of the fundamental laws of our Universe cannot but lead to a wealth of new possibilities, both directly and indirectly. Projects at CERN (the European Organization for Nuclear Research) chasing the Higgs and other particles have already delivered the World Wide Web as a spin-off; only history will reveal what else will come.

In my own research field, astrophysics, we see the same interplay. Long-term investment in radio astronomy in Australia and the search for exotic states of matter such as black holes ultimately led to a thriving export business in specialised antennas, the facilitation of wireless computing worldwide, and a successful bid for the world's largest radio telescope, the Square Kilometre Array.

This report is about ensuring that the process of strategic investment in teaching and research in physics in Australia continues over the next 10 years, so that Australia remains a strong member of the world's physics community and reaps the associated intellectual, economic and social rewards.

The Physics decadal plan 2012–2021: building on excellence in physics is ambitious but achievable. It calls for significant investment in invigorating physics education at all levels, addressing physics skills shortages, boosting capacity in physics research, and supporting international collaboration in physics, particularly with our Asian neighbours.

In times of stringent fiscal constraints, it may be tempting to forego investment in the fundamentals of our economy — education, research and development. But this is a false economy, as it forestalls building of capacity to meet the challenges of the future. In the end, investment in this plan is a small price to pay for outcomes upon which our nation will be increasingly dependent: helping us generate and manage diminishing energy resources; understanding and coping with climate change; developing better medical imaging, diagnosis and treatments; building a high technology industry base; and interpreting the laws of the Universe and our place in it.

I commend the *Physics decadal plan 2012–2021* to you.

Professor Brian Schmidt FAA
(Nobel Prize in Physics, 2011)
Research School of Astronomy and Astrophysics, Mount Stromlo Observatory
Australian National University

From the working group convener

Physics is a fundamental science that underpins other disciplines such as engineering, computer science, chemistry and medicine. Physics provides the fundamental understanding that allows development of new technologies and tools for advances in all of science and technology and builds capacity for new industries and business. Investment in physics provides returns in many forms and on many timescales.

Physicists are renowned for being solution finders. Solutions can have unexpected impacts in new areas of activity. Examples include new phase contrast biomedical imaging techniques and cancer treatments, broadband communication, solar cells, green energy and power, organic photovoltaics, nanotechnology and advanced materials. New companies such as Bluglass (LED technology), Quintessence (information technology security systems) and SRL Plascon (electric plasma based hazardous waste destruction) seek to bring products to market. Physicists support interdisciplinary research conducted on major national facilities such as the Australian Synchrotron, the OPAL reactor, within hospitals and CSIRO, DSTO and other major laboratories.

To face the big challenges of the future, excellence in physics literacy is required. Physics graduates move into many professions. Some of these, such as teaching, research in universities and government laboratories, and drivers of high technology industries, require discipline-specific knowledge. However, physics graduates are also keenly sought for a wide range of government and industry positions in which their ability to think critically, analyse data and solve abstract problems is their key credential for employment. Australian physicists can be found in academic institutions, laboratories and industries around the globe.

Building on excellence in physics: underpinning Australia's future is the product of a research project by the physics community to survey the discipline of physics in Australia and identify near and far opportunities. It builds on the 1993 review of physics in Australia. The 1993 report contained 38 recommendations aimed at making Australian physics stronger, and defined a pathway to a more competitive Australia. It addressed these issues based on five elements: investing greater resources nationally in research and innovation; improving access to the tools needed for the advancement of physics; training for future needs; lifting the status of physics in the community; and planning for the future. The 1993 plan contributed to raising the level and impact of optics research in Australia and setting optics as an ARC priority area. This has contributed to the very strong present-day role of optics research in Australian physics. Nearly 20 years later the five elements of the 1993 plan are still just as important.

The 2011–2012 plan process has been managed by the Physics Decadal Plan Working Group under the auspices of the Australian Institute of Physics and the Australian Academy of Science. Throughout the process it was clear that Australian physicists are well connected to the international enterprise of physics and that there are many opportunities to better capitalise on those connections. People everywhere were concerned about supporting our physics teachers. Australia has been relatively lightly touched by the global financial crisis and that, thanks to the investments made over the past 20 years, makes Australia a desirable place to live and work. Australia has unique opportunities in the competition to attract and develop the best human capital into physics. This plan aims to identify and build on those opportunities.

Professor DN Jamieson
July 2012

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Abbreviations

AIP	Australian Institute of Physics
AMSI	Australian Mathematical Sciences Institute
ANSTO	Australian Nuclear Science and Technology Organisation
ANU	Australian National University
APA	Australian postgraduate award
ARC	Australian Research Council
CAMS	ARC Centre of Excellence for Antimatter-Matter Studies
CERN	European Organization for Nuclear Research
CFC	chlorofluorocarbon
CLFR	compact linear Fresnel reflector
CO_2	carbon dioxide
CSF	critical success factor
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DIISRTE	Department of Industry, Innovation, Science, Research and Tertiary Education
DSTO	Defence Science and Technology Organisation
ERA	Excellence in Research for Australia
EU	European Union
FOR	field of research
GDP	gross domestic product
GMR	giant magneto resistance
GPS	global positioning system
ICSU	International Council for Science
IP	intellectual property
IPRS	international postgraduate research scholarship
ITER	International Thermonuclear Experimental Reactor
LAN	local area network
LIGO	Laser Interferometer Gravitational-Wave Observatory
NCRIS	National Collaborative Research Infrastructure Strategy
NMI	National Measurement Institute
OECD	Organisation for Economic Co-operation and Development
OPAL	Open Pool Australian Lightwater Reactor
PCB	polychlorinated biphenyl
PISA	Program for International Student Assessment
SET	science, engineering and technology
STEM	science, technology, engineering and mathematics
TIMSS	Trends in International Mathematics and Science Study
UK	United Kingdom
USA	United States of America
UWA	University of Western Australia

Executive summary

Physics is a core discipline that underpins our understanding of both the world around us and the technological advancements that benefit of our society. Physics is an intellectually demanding science that requires high mathematical and theoretical literacy, which provides a challenge for the teaching of physics at all levels and for attracting the best students into the discipline to maximise the benefits for the nation. More than any other discipline, much of physics research requires large, often interdisciplinary teams, extensive financial and human capital and strong global engagement in order to make an international impact. In this Australia is critically dependent on a large cohort of early career physics researchers supported by research funding agencies. Schemes that support these resources are essential.

Key findings

- Physics is one of Australia's research strengths, and produces significant spinoffs to industry and society. This success is built on research funding from schemes such as the Australian Research Council (ARC), and support of government research organisations. Continued funding of physics research is essential to maintain Australia's standing in the international community as punching above its weight in innovation and technology.
- There is a worrying decline in the uptake of physics by students at secondary level. This decadal plan suggests the introduction of a requirement that secondary school teachers are trained in physics to three years above the highest level at which they are required to teach it. This is so that physics teachers will have a perspective to inspire students to studies beyond the level at which they are being taught. Physics teachers must also be properly supported with the resources needed to do their job, and appropriate recognition must be given for the contribution made by teachers to nurturing a passion for physics in the next generations.
- Ongoing campaigns to promote the wide spectrum of available career paths to physics students should be initiated as a priority.
- A critical component of any country's science and innovation system is government support for research internationalisation. The current paucity of funding opportunities in Australia places us at a serious competitive disadvantage. The urgent establishment of a replacement for the International Science Linkages scheme to enable access to major international physics facilities and research opportunities and to enable engagement with major overseas funding schemes is required.
- A large proportion of senior physicists currently contributing to high-quality research outputs that seed the physics innovation system, and who are responsible for training the next generation of physics leaders, are approaching retirement. Unaddressed skills shortages in the physics research sector threaten the maintenance of Australia's technological capability, our participation in discovering solutions to global challenges, and our ability to work in international and interdisciplinary teams. These are strong and compelling grounds to implement mechanisms to train, attract and retain physicists in Australia.
- Given the importance of physics to other scientific disciplines and to a multitude of industries, the National Mathematics and Science Education and Industry Adviser located within the Office of the Chief Scientist must work with the physics community to address physics-specific challenges.
- Major benefits can be derived by facilitation of cross-sector mobility between higher education institutions, government research agencies, industry and business.
- The current mechanisms and metrics used to measure performance and for career progression are out-dated and need urgent review. The current system rewards publication-related activities and penalises researchers who engage in important activities such as entrepreneurial and commercial activity, and activities that broaden skills such as assisting government with policy formulation.
- The way physics is practiced is changing and this must be reflected by the science system in Australia. Research funding programs must allow the participation of physics in multidisciplinary consortia to address problems of national importance and to tackle ambitious research projects.

- Targeted strategies to attract and retain highly skilled but vulnerable members of the physics community should be adopted as a priority. Vulnerable physicists include women, early-career researchers, those who wish to re-enter the physics workforce after taking time out for family or to broaden skills, and Indigenous people.
- The physics decadal plan needs an agency with the responsibility for implementation of the recommendations of the plan. This agency will coordinate the effort of the various stakeholders and develop the necessary processes to act on the issues raised in this report. There are many agencies already in existence that have a stake in promoting the cause of physics in Australia. The agency with the best resources for coordinating the effort is the National Committee for Physics of the Australian Academy of Science and this agency is therefore recommended to take custody of the plan and drive the implementation strategies.

Objectives

The *Physics decadal plan 2012–2021* presents the Australian physics community's strategic vision for the ten years 2012–2021. It outlines future growth opportunities taking into account the importance of physics education, physics in our society, the importance of international engagement, and that science and technology are important for our future.

Physics always presents challenges and opportunities. In the near future these will include the implications of the Higgs boson and its even more exotic partners — room temperature superconductors, dark matter, quantum coherence in room temperature processes, efficient ways to transform energy, and sleek devices to interface with the human body.

Today, the impact of physics is reflected in the extraordinary penetration of information technology into all aspects of everyday life. It is almost impossible to do anything without leaving digital footprints in server farms and databases. In a random café anywhere in the world many of the clientele will be employing the physics of the element silicon, properties of electricity and magnetism from Maxwell's equations, the passage of light through carefully crafted glass fibres, the equations of general relativity that describe how gravity shapes space and time for the global positioning system (GPS), and other fundamental physics principles to surf the web, read a newspaper or keep in touch with friends and family.

The 2012–2021 decadal plan is deliberately ambitious, but achievable. It speaks to the physics community's notable strengths and proposes that these be the underpinnings of achieving and sustaining physics excellence in Australia in the next decade. With this plan, the Australian physics community unites and stands committed to work for the national interest.

Implementation of the plan is the responsibility of all contributors to the physics innovation system (see table 1, page 2). Importantly, the plan will assist policy makers, politicians and industry leaders as decisions are made around investments in physics education, research, infrastructure, and enterprise. The anticipated gains will be shared and include greater commercialisation success and superior innovation through the intermingling of pure and applied research endeavours. The government, business and community sectors are not only daily beneficiaries of the outputs from physics, but they also play an important role in defining demand.

Three opportunities for physics in Australia

Extensive consultation with the community conducted by sub-discipline working groups identified three broad areas of opportunity for the future of physics in Australia. These are the new quantum revolution; the quest for new physics and new symmetries; and physics in the society in which we live.

1. THE NEW QUANTUM REVOLUTION

At a time when we are developing an ability to exert control over quantum processes, new applications of quantum mechanics are being revealed in areas such as the storage, transmission and manipulation of information. Quantum mechanics is also providing a deeper understanding of biological processes.

In the previous century, quantum physics was responsible for the invention of the transistor, the television, nuclear energy sources, and other life-changing technologies. It is anticipated that the 21st century will deliver a second wave of the quantum technological revolution where concepts of the microscopic world will again provide unprecedented benefits to society.

Australian quantum physicists engage in research in areas including semiconductors, neutral atoms, ion traps, superconducting circuits, opto-mechanics, photonics and quantum dots. This amounts to great strength for a country the size of Australia with the challenge to maintain the necessary depth.

Continued support for programs focused on research excellence, including centres of excellence and research fellowships, is required to maintain this strength. Strong engagement with the international physics community through the exchange of people and collaborative research projects is also needed to enhance Australia's capability and relevance.

2. THE QUEST FOR NEW PHYSICS AND NEW SYMMETRIES

The electron and photon and their quantum mechanical description were once purely the domain of fundamental physics, but now form the basis of multi-trillion-dollar industries in electronics, communications, computing and manufacturing. The investigation of subatomic particles and the farthest reaches of the Universe, and the theoretical explanations required, will probably yield new technologies we cannot yet imagine. Studies of the physics of the extremely small and the extremely large — at the scale of the particles that form the most fundamental building blocks of matter and of the large structures which form the Universe — are the domain of the 21st century.

Mechanisms to allow Australian physicists to continue to test their ideas and collaborate with international teams at experimental facilities (such as the Large Hadron Collider) and work on international projects (such as the Square Kilometre Array) must be preserved and further developed.

3. PHYSICS IN THE SOCIETY IN WHICH WE LIVE

There will be rapidly increasing opportunities in the next decade to harness the knowledge of physics to serve our society. Examples include generating electricity with minimal environmental impact, advanced tools for medical imaging, diagnosis and therapy, and informing government decision making on issues of long term and global significance. Increasingly close collaboration in multidisciplinary teams will be required to meet these challenges.

For example, assessing and addressing the challenge of climate change will require sound physics and the collaboration of teams with expertise across the innovation spectrum. While low carbon sources of power are becoming more substantial, they still remain stubbornly minor in proportion to demand.

The eternal quest to improve health and diagnose disease has been a constant driver in the development of new imaging technologies, most of which have their origin in fundamental physics research. In Australia medical physics has made substantial contributions at both the national and international levels to radiation therapy and oncology, medical imaging, nuclear medicine, nano-dosimetry and radiobiology, as well as to the development of medical devices such as the internationally renowned cochlear Implant. Bionic vision is a near-term goal that will be made possible through advances in information processing and the machine–human interface.

Supporting all aspects of physics in the society in which we live requires an excellent education system that inspires young people to study physics, to choose careers in physics and to make decisions about the future of our society based on sound physics principles.

Four critical issues for the future of physics

The physics decadal plan reviews the current position of physics in Australia, and identifies future directions and opportunities for Australian physics in the global context by exploring and making recommendations in four main areas:

1. ACHIEVING A PHYSICS-LITERATE WORKFORCE AND COMMUNITY

Addressing the need to improve the teaching of physics at all school levels is a fundamental requirement for achieving a physics-literate workforce and community. To ensure a steady supply of physicists in the immediate future, we need to improve the recognition of the contribution made by teachers to nurturing a passion for physics in the next generations. It is essential that physics be taught by well-trained and enthusiastic teachers properly supported by the resources needed to do their job.

DECADAL OBJECTIVES

- Attract and retain students in physics at all educational levels.
- Increase the quality and number of appropriately qualified physics teachers across the school sector.
- Reduce the gender differential in physics competency at all school levels.
- Improve physics literacy in the general community.
- Improve the use of the physics evidence base to inform policy development.

A focus on teaching physics topics in primary school and the early middle school years is required to reverse the current trend of lower performance of female students in physics and mathematics.

2. REALISING HUMAN CAPITAL IN PHYSICS

There is significant evidence that by 2020 the demand for researchers will outstrip supply. Unaddressed skills shortages in the physics research sector threaten the maintenance of Australia's technological capability and our ability to work in international and interdisciplinary teams.

A significant proportion of those currently responsible for maintaining the high-quality research outputs that seed the physics innovation system are currently in senior positions. Opportunities must be provided for the next generation of research leaders to continue to produce research outputs of excellence and impact, and train the succeeding generation. Targeted strategies to attract and retain highly skilled but vulnerable members of the physics community must also be adopted. This includes women who are less likely to choose and/or progress a career in physics; early-career researchers who have little job security due to their high dependence on short-term competitive grant funding; those who wish to re-enter the physics workforce after taking time out for family or to broaden skills; and Indigenous people who wish to access and complete advanced studies in physics. Equally, organisations should be required to report on their activities to ensure equitable practices that can lead to the removal of disadvantage for vulnerable sections of the workforce.

Career management is an essential activity to retain talented physicists. Employment prospects and the variety of exciting career paths available to trained physicists should be well documented and promoted.

Strategies to improve collaboration between industry and research organisations nationally and internationally must be devised and adopted. Issues such as intellectual property management by academic institutions and improved understanding of factors that affect the business environment (such as shareholder and customer demands) are central to improving partnerships between industry and academia. A key factor to improving collaboration between industry and the research sector is recognition of the weaknesses associated with the publication-based metrics applied in Australia which do not capture or reward entrepreneurialism and interactions with industry. Currently researchers are not always rewarded for pursuing non-traditional career paths. It is critical to recognise and reward efforts made to partner with industry or other disciplines, commercialise, or assist government with policy formulation.

Strengthening interactions and scientific collaboration with cross-disciplinary teams will provide diverse employment opportunities for graduates and allow industry to boost their research and development efforts and investment.

3. BUILDING ON PHYSICS RESEARCH AND INVESTMENT

Research productivity amongst physicists could be improved by reducing the time invested in preparing and assessing applications for competitive grant schemes. Implementation of a two-stage 'white paper' system would make the process more cost and resource efficient. 'Field of research' classifications and related metrics should be used to

DECADAL OBJECTIVES

- Address skills shortages in the physics research sector by creating a healthy pipeline of physics-trained professionals.
- Maintain Australia's excellent international reputation in physics and high-quality research output.
- Train, attract and retain physicists to and in Australia by maintaining and promoting the quality of Australian physics research groups and Australian research strengths.
- Attract and retain vulnerable members of the physics community, including women, Indigenous Australians, early-career researchers, and those taking career breaks to develop valuable skills.
- Facilitate productive partnerships and mobility between academia and industry.
- Enhance industry-driven applied and commercial research.
- Ensure greater participation of physics in interdisciplinary research.

A 'white paper' in this context is a brief, authoritative proposal that helps solve a problem as the first stage of a funding round. The white paper is used to inform the readers and help people make decisions about which proposals are selected for submission of a detailed research proposal to implement a new research project.

DECADAL OBJECTIVES

- Improve efficiency of funding agency processes to maximise impact of public investment and improve agility
- Increase the global competitiveness and impact of the Australian physics research sector by long-term investment in research infrastructure and human resource capabilities
- Diversify physics research funding sources
- Find ways to support 'shovel ready' ARC proposals with a sustainability theme assessed as worthwhile by the rigorous ARC processes through liaison between the ARC secretariat and the managers of the Clean Energy Finance Corporation
- Ensure overhead and operational costs of infrastructure are included in infrastructure funding schemes.

reflect accurately the current physics sub-disciplines and more importantly, their different publication and citation modalities.

Maintaining and expanding research infrastructure, including super-computing infrastructure, is essential to attract the world's best and brightest physicists and national and international collaborators. Staff, operational and maintenance costs must be factored into infrastructure investment for Australian physics research to remain at the cutting edge and to maintain international collaborations.

In some sub-disciplines of physics, such as theoretical physics and mathematical physics, physical infrastructure is not required. However, theoretical physicists do require a critical mass to sustain capability and ensure international visibility. Small postgraduate numbers at any one institution makes teaching advanced graduate courses uneconomical. The establishment of an Australian Theoretical Physics Institute would provide the necessary infrastructure to support and coordinate theoretical activities in physics. The current infrastructure funding guidelines should be amended to provide for this type of investment.

4. ENGAGING IN THE INTERNATIONAL ENTERPRISE OF PHYSICS

A high level of international collaboration has enabled Australian physicists to capitalise on international investments made in existing research

DECADAL OBJECTIVES

- Consolidate existing bilateral schemes and develop new schemes for international collaboration, including schemes to allow Australian researchers to become funded partners in US and European Union initiatives
- Strengthen international collaboration with countries in the Asia–Pacific region, including China, India, Japan and Korea
- Make international research participation central to Australian physics.

infrastructure that is often beyond the means of any single nation to build and maintain. Ongoing coordinated effort and government support are necessary to establish and maintain research relationships with leading research organisations and nations, and to build and expand relationships with emerging nations.

Collaboration within the Asia–Pacific region is an increasingly important policy issue for Australia. Of particular importance is collaboration with China and India as Australian research competencies complement the technological needs, strengths and capacity of these nations.

Consistent with the Australian Academy of Science's position paper, *Australian science in a changing world: innovation requires global engagement* [1], it is essential that resources are provided for collaborative innovation projects, for programs supporting early to mid-career researchers, and for building strategic partnerships in branches of physics. In addition, investment is required in improved awareness campaigns, improved governance and improved diplomacy for Australia to adapt to future changes in the global landscape of physics.

Summary of recommendations

Each recommendation in this summary is addressed in the four critical issue chapters that comprise the body of the plan.

RECOMMENDED ACTIONS AND PATHWAYS

a) Quality teaching — quality students

- Establish a scholarship scheme to encourage excellent physics graduates into a secondary education teaching career.

1 www.science.org.au/reports/documents/Innovationrequiresglobalengagement.pdf

- Consult to ensure the physics component of the national curriculum is founded on rigorous analytical and quantitative reasoning, and encompasses the fundamentals of physics; and develop a formal process to second physicists to serve on panels developing the curriculum.
- Require that secondary school teachers are trained in physics to three years above the highest level at which they are required to teach physics. This corresponds to first-year university physics for years 7–10 teachers and a major in physics for years 11–12 teachers.
- Endorse an undergraduate science degree together with a teaching qualification as the preferred qualification option for years 7–12 physics teachers.
- Require science education training as an integral part of the teacher training for future primary school teachers.
- Resource universities to provide programs that up-skill and update school physics teachers as part of their professional development. This should include resources for secondary school physics teachers to take sabbatical leave to participate in undergraduate teaching programs within the university sector.
- Introduce options for science, mathematics and physics teachers to allow them to study part-time for a teaching MSc.
- Continue ongoing support for the development and implementation of the Australian Academy of Science's primary school program *Primary Connections* and its junior secondary school program *Science by Doing*. These award-winning approaches to professional learning and school curriculum resources have been shown to have a positive impact on the quality and quantity of science taught in schools.
- Encourage school programs such as *Scientists in Schools*, *STELR* [2], *Science and Engineering Challenge* [3] and *SPICE* [4] that promote contemporary quality school science learning.
- Reward excellence in physics teaching. A panel of leading teachers should be convened to identify the best process, perhaps under the auspices of the Australian Institute of Physics (AIP) Education Convener.
- Introduce teaching bursaries to support students interested in teaching physics to gain qualifications.

2 http://stelr.org.au/

3 www.newcastle.edu.au/faculty/engineering/community-engagement/challenge/

4 www.clt.uwa.edu.au/projects/spice

- Start public campaigns to raise the status of teaching as a profession, modelled on the successful Victorian State Government campaign.
- Establish a joint-academies taskforce to harness the strengths of e-learning in tertiary institutions with a view to developing the next generation of teaching technologies jointly across the sector. This will include the establishment of a competitive teaching and learning scheme to aid in the transformation of education in science, technology, engineering and mathematics (STEM) and the development of metrics to evaluate STEM education.
- Identify and address the underlying causes of the under-representation of girls in physics at all levels of school education.
- Promote the spectrum of available career paths to students to enable them to make informed decisions about career choices.
- Provide career advisory services particularly for school students (but also university undergraduates and graduates) so they can make informed choices about future career pathways, such as teaching, research, government or industry employment.

b) Internationally competitive Australian physics undergraduate and postgraduate students

- Broker agreements between Australian higher education providers to ensure that the Australian physics PhD is comparable in the breadth, depth and duration of training to those in the USA and the EU, particularly by providing the resources for the inclusion of postgraduate coursework as a key component for higher degree by research training.
- Merge the Australian postgraduate award scholarships scheme with the international postgraduate research scholarship scheme to open up the scholarship pool to all domestic and international students.
- Provide a balance of learning experiences between theoretical, experimental, observational and computational physics to ensure employment readiness of graduates not only for research but also for industry and business. This will include a process for consultation with key employers to better understand their needs.

c) Valuing and promoting physics

- Commit resources from the higher education and research sectors to support high-quality outreach programs with long-term impact that can reach and engage Australians.

- Develop programs and commit resources to promote the value of physics and physics education and careers to school students, parents, industry, universities and government bodies.
- Ensure the National Mathematics and Science Education and Industry Adviser located within the Office of the Chief Scientist works with the physics community to address physics-specific challenges.

d) Equitable career pathways and removing disadvantage

- Provide equitable access to career opportunities by consistently enforcing research opportunity and performance evidence guidelines in assessing candidates for research positions and for internal and grant funding.
- Implement initiatives to recruit, retain and promote women and create an environment in which all staff can achieve their maximum potential.
- Reassess the standard performance metrics upon which career progression largely depends.
- Improve the academic preparedness of prospective Indigenous students; and improve personal and financial support once enrolled.
- Develop alternative pathways into higher education for Indigenous students
- Reassess conditions for travel support. In the case of the ARC Future Fellowship Scheme (and its successors) the restrictions on non-fellow travel support are recommended to be lifted. At present restricting travel support only to the fellow discriminates against fellows who cannot travel because of carer responsibilities. Allowing fellows to use their ARC travel funds to support visits of key collaborators who will advance the cause of the project will remove this discrimination.

e) Partnerships between industry and academia

- Provide joint postdoctoral (as opposed to PhD) positions in industry, jointly funded by government, university and industry.
- Develop a 'Physics in Industry' model for constructive and lasting relationships between industry, business and the higher education sector based on the successful 'Mathematics in Industry Group' run by the Australian Mathematical Sciences Institute (AMSI) [5]. This could be done by the Australian Institute of Physics and the Australian Academy of Science National Committee for Physics.
- Develop models for facilitating cross-sector mobility between higher education institutions, government research agencies and industry and business. This includes developing mechanisms and metrics that facilitate entrepreneurialism and commercialisation of research within research organisations without penalising career prospects.
- Convene, under the leadership of government, a summit or workshop with the aim of developing an understanding of mutual expectations of government, industry and academia, and to develop more effective modes of interaction and collaboration.
- Better manage intellectual property held by academic institutions.
- Improve understanding by physics researchers of factors affecting businesses (such as shareholder and customer demands).

f) The power of cross-disciplinary research

- Encourage the participation of physics in interdisciplinary consortia to address problems of national importance by encouraging research funding programs to aggregate critical mass without discipline restrictions.
- Develop schemes that support large, coordinated multidisciplinary teams and ambitious research projects.

g) Efficient, agile, fair and sustainable research funding

- Minimise the administrative burden and make efficient funding agency processes by streamlining the ARC grant application process, with consideration of moving to a two-stage 'white paper' system.
- Simplify funding schemes that support physics research, including a simplified process for grant renewal beyond the initial three years for projects of demonstrated significant achievement.
- Collaborate with the major funding agencies to improve agility of the funding process to enable responsiveness to international research opportunities, some of which arise at short notice, by the introduction of a new international collaborative research scheme.
- Ensure that there are funding schemes to support large collaborative centres of excellence in physics funded adequately at the top end of discipline funding. Physics research in areas of global and technological importance specifically requires large interdisciplinary teams to make an international impact.

5 www.amsi.org.au/

h) Infrastructure investment to remain at the cutting edge

- Provide ongoing funding for the National Collaborative Research Infrastructure Strategy (NCRIS) process to support major national physics infrastructure upgrades and operational costs, including the provision of qualified support staff.
- Broaden the ARC definition of 'infrastructure' to accommodate the non-physical infrastructure, critical for theoretical and mathematical physicists.
- Establish a 'Landmark Funding Scheme' to support participation in major international research initiatives (the order of $100 million or greater) that fall outside the scope of current funding schemes.
- Develop a system to allow small to medium enterprise to access supercomputers to bypass the cumbersome prototyping phase in product development.

i) Metrics and coding for the 21st century

- Develop metrics for academic activities that are broader than those based simply on publication output and citations, including measures of interaction with industry, commercialisation and the commercial impact of applied research.

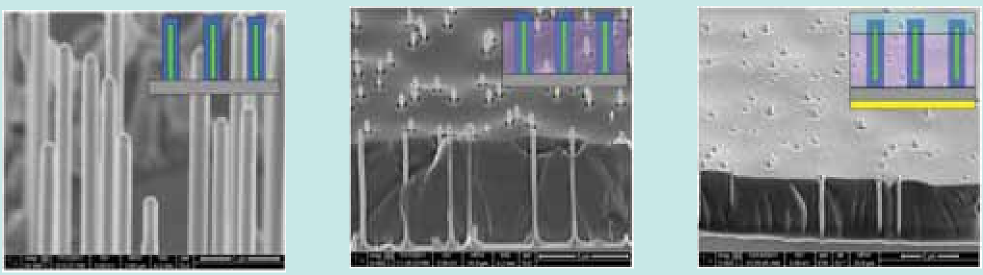
NANOWIRES FOR NEW-GENERATION LASERS, SENSORS AND SOLAR CELLS

Nanophotonics, the fusion of nanotechnology and photonics, is an emerging field offering exciting challenges for fundamental research and providing major potential for the delivery of new technologies. The Nanowire Team at the Australian National University (ANU) is working to understand the synthesis of nanowires, light interaction in these materials and how these properties can be used to develop a new generation of optoelectronic devices such as nanowire lasers, nanowire photodetectors and nanowire solar cells. Fabrification of advanced metamaterial nanostructures with application to photonics is being undertaken with another group at ANU. With 150+ papers published in top international journals, the results achieved to date have attracted enormous local and international interest and are the stepping stones to a new generation of optoelectronic devices monolithically integrated with microprocessor/CMOS-based subsystems.

The long-term aim of the ANU nanowire research team is to use the physical understanding of nanowire synthesis and light interactions in these materials to explore novel optoelectronic devices such as nanowire laser arrays, ultra-compact metal cavity nanowire lasers, microcavity resonators for polariton lasers, high efficiency nanowire solar cells and photodetectors, and nanowire optical interconnects.

See **www.physics.anu.edu.au/eme**.

Schematics of high efficiency nanowire solar cell fabrication



(a) (b) (c)

- Develop an expanded set of metrics for university staff that can be used for tracking progress and process improvements (such as equity-related activities, achieving diversity of funding, meeting milestones in attracting new talent, developing collaborative programs etc.). ARC programs, such as Linkage, already recognise this to some extent.
- Ensure that the research metrics and classifications used accurately reflect the current physics sub-disciplines and more importantly, their different publication and citation modalities.
- The Australian Bureau of Statistics and the Department of Industry, Innovation, Science, Research and Tertiary Education (DIISRTE) re-examine field of research codes for their appropriateness in the current scientific environment.

CSIRO'S WIRELESS LAN TECHNOLOGY

John O'Sullivan FAA led the Commonwealth Scientific and Industrial Research Organisation (CSIRO) system design team for the world's first 802.11a (WiFi) chipset that was subsequently developed and commercialised by Radiata Networks. He received a Bachelor of Science in Physics from Sydney University in 1967, and a Bachelor of Engineering with first class Honours and the University Medal in 1969 and a PhD in Electrical Engineering in 1974, both from the same institution.

CSIRO's wireless invention lies at the heart of what is now the most popular way to connect computers without wires. Forecasters predict that there are likely to be more than a billion devices sold worldwide over the next few years using this technology. The invention came out of CSIRO's pioneering work in radioastronomy. That work involved complex mathematics known as 'fast Fourier transforms' as well as detailed knowledge about radio waves and their behaviour in different environments.

Indoor environments are particularly difficult for the rapid exchange of large amounts of data using radio waves. CSIRO solved these problems in a unique way at a time when many of the major communications companies around the world were trying, but with less success, to find a solution to the same problem.

CSIRO's invention was granted a US patent in 1996. There are corresponding patents in 18 other countries.

The technology was first embodied in an industry standard in 1999 (called IEEE 802.11a) and later in other standards (IEEE 802.11g and IEEE 802.11 draft n).

Dr O'Sullivan's career spans two disciplines, physics and engineering, and work in both government-funded research and industrial research. After completing his PhD in Sydney he took an appointment in the Foundation for Radio Astronomy in the Netherlands (now ASTRON). He went on to become the head of their engineering group, making major contributions in the electronics and signal and image processing areas.

In 1983, he returned to Australia for research at CSIRO and played an important early role in the initial conception of the Australia Telescope receiving systems. He was primarily charged with setting up a new signal processing group at the Division of Radiophysics.

This group under his direction set out to find applications of processing skills and technologies for the wider community and led to the group making significant contributions, together with various commercial partners and customers, in areas such as image processing for medical and geophysical applications, underground mine safety, communications systems and radar processing systems.

After his demonstration of the wireless local area network (LAN) system, Dr O'Sullivan left CSIRO in 1995 to join News Ltd as their Australian Director of Technology. During this period, he was a member of the Prime Minister's Science, Engineering and Innovation Council working party 'Connecting Australians: opportunities for a new wireless age'.

- **j) International enterprise of physics**
- Establish a replacement for the *International Science Linkages* scheme to enable access to major international facilities and research opportunities and to enable engagement with major overseas funding schemes such as the EU Framework Programs.
- Establish co-funding agreements with international grant agencies (e.g. EU and the US National Science Foundation) to allow Australian researchers to be partners in major international collaborations.
- Establish a replacement for the International Researcher Exchange Scheme that promotes two-way exchange at the level of individual researchers essential for rapidly developing fields.
- Ensure Australian physicists are able to provide inputs on international panels and agencies that develop international policy.

The review panel

The exposure draft of the physics decadal plan was reviewed in 2012 by a panel of leading physicists and scientists [1]. Their advice and guidance is gratefully acknowledged.

Professor Aidan Byrne	Dean, Faculty of Science	Australian National University, ACT
Professor Peter Drummond FAA	Centre for Atom Optics and Ultrafast Spectroscopy	Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, VIC
Dr Marc Duldig	President, AIP	School of Mathematics and Physics, University of Tasmania, TAS
Dr Bob Frater FAA	Vice-President, ResMed	ResMed Innovation, Bella Vista, NSW
Professor Bruce McKellar FAA	Chair, ICSU Regional Committee for Asia and the Pacific, President-Designate of the International Union of Pure and Applied Physics	School of Physics, University of Melbourne, VIC
Professor Gerard Milburn FAA	Director, ARC Centre of Excellence for Engineered Quantum Systems and ARC Federation Fellow	School of Mathematics and Physics, University of Queensland, QLD
Professor Mary O'Kane	NSW Chief Scientist	Office of NSW Chief Scientist and Engineer, Sydney, NSW
Dr Adi Paterson	Chief Executive Officer, ANSTO	Australian Nuclear Science and Technology Organisation, Kirawee, NSW
Professor Geoffrey Taylor	Director, ARC Centre of Excellence for Particle Physics at the Terascale	School of Physics, University of Melbourne, VIC
Professor Anthony Williams	Associate Director, Centre for the Subatomic Structure of Matter, Chief Investigator, ARC Centre of Excellence for Particle Physics at the Terascale, Executive Director, Australian Research Collaboration Service	School of Chemistry and Physics University of Adelaide, University of Adelaide, SA

Further reviews were provided by the National Committee for Physics listed in the acknowledgements.

1 Affiliation at May 2012

‘Physics is a foundational and fundamental field that makes a significant contribution to the health of the Australian economy for its ability to generate the new knowledge, technology and high-quality human capital underpinning the innovation system. The last strategic overview of physics in Australia was conducted back in 1993 under the guidance of the Australian Research Council. For such a dynamic and fast-moving research field it is essential that a review of the current status of physics in Australia is conducted to evaluate the opportunities available for the future growth of the discipline. Importantly, this will allow us to reposition ourselves and determine what is required to make physics an even better contributor to Australian and global science.’

Professor Michelle Simmons FAA
Chair, National Committee for Physics, Australian Academy of Science

Introduction

The physics decadal plan presents the Australian physics community's strategic vision for the ten years 2012–2021 and beyond. This plan builds on the 1993 review of physics in Australia. Much has progressed since 1993 and physics continues to give rise to new technology and be a key enabling science.

Australian physicists continue to make fundamental contributions to international efforts to understand the natural world. At the same time, physics is contributing to society and the economy in Australia, to build high value exports, improve health, public safety and community services, increase national security, and devise wiser policies which can guide sustainable economic development while protecting the environment for future generations.

Since the 1993 review the landscape has changed significantly. In 2011, Australia celebrated the award of the Nobel Prize in Physics to Professor Brian Schmidt, the last Australian Nobel Prize in physics being in 1915. In the recently announced discovery of the Higgs boson at CERN, the role of Australian physicists has been acknowledged. Australian physicists have also supported the successful bid to have a significant part of the Square Kilometre Array in Australia and will be critical to its implementation and long-term operation.

This review of the current status of physics in Australia was done in the light of major achievements such as these. The review seeks to identify major opportunities for the future contribution of physics to society, the economy and the advancement of knowledge.

Such a review must acknowledge the opportunities for stronger engagement with our Asian neighbours. The present transformative growth in Asia presents opportunities for stronger engagement in science, technology and education [1]. Internationally, knowledge generation and technology are seen as tools for recovery from the global financial crisis. US President Obama's Chief Science Adviser, John Holdren sums this up eloquently: '*Science, technology and innovation have been the primary drivers of [American] economic growth and productivity growth for decades..... No matter how severe the fiscal constraint, this is not the time to stop investing in the drivers of the economic growth we need for recovery, for job-creation, for economic growth going forward.*'

Australian Government measures also provide a new landscape. Significant amongst them are policy targets of 40 per cent of 25 to 34 year olds attaining a bachelor degree or higher by 2025 with the milestone of 35 per cent already reached in 2011. These policies present opportunities to broaden and deepen knowledge of physics in our society.

One of the goals of the decadal plan is to provide policy makers with a vision of a vibrant future for the Australian economy and for Australian society resulting from an environment in which physics continues to thrive.

The decadal plan also aims to stimulate wider deliberations on the future direction of Australian education, science, research, and innovation. As such, it highlights three areas of opportunity for physics in Australia: the new quantum revolution; the quest for new physics and symmetries; and physics in the society in which we live.

The Australian physics community is united in its support of this decadal plan and in its belief that physics has a major role to play in the national interest.

Audience, stakeholders and implementation

The physics decadal plan sets a strategic framework for funders, practitioners, users, teachers and students of physics. Implementation of the plan is the responsibility of all contributors to the physics innovation system (table 1). Importantly, the plan seeks to assist policy makers, parliamentarians, and industry leaders in the setting of policies and decisions on investments in physics education, research, infrastructure, and enterprise.

1 asiancentury.dpmc.gov.au/terms-of-reference

Timely implementation is critical to the plan's effectiveness and success. The broader physics community is made up of a number of stakeholder groups. These include secondary schools, the higher education sector, researchers, industry and business, government, and domestic and international communities. Each of these stakeholder groups has a role to play in the realisation of the decadal plan.

Stakeholders can also expect returns from the implementation of the plan. They include increased commercialisation success and greater innovation through the intermingling of pure and applied research endeavours. The government and community sectors are daily beneficiaries of the outputs from the physics community, as well as playing an important role in defining demand. The discipline stands to gain from appropriate promotion of physics to these stakeholders and in particular encouraging the public to engage with how physics shapes our daily lives and its potential for new technologies.

The interconnectedness of the various sectors of the physics community and the wide dispersal of people with physics training in all sectors of our community increases the complexity of implementing the recommendations in this plan. However, this also provides significant opportunity to embrace engagement between the different sectors.

At present the 'ownership' of physics in Australia is distributed between a number of organisations and committees each of which play important roles. These include the National Committee for Physics of the Australian Academy of Science, the Australian Institute of Physics, and Science & Technology Australia, along with several sub-discipline specific organisations where physicists play an important role. The resources available in each organisation vary considerably and the regular activities and respective missions overlap to some degree with the tasks required to implement the decadal plan. However, for the plan to be effective it requires a more formal implementation strategy. The decadal plan should be overseen by a group with the specific responsibility for implementation of the plan. In particular, the group would coordinate the effort of the various critical components of the physics community and stakeholder groups. One possible

Table 1: Outline of contributors to the physics innovation system

Contributors and stakeholders in the physics innovation system	Critical success factors to support a vibrant and sustainable physics system in Australia
Primary schools	Provide teacher training including strong science and maths components; identify and support teaching resources that are age appropriate
Secondary schools	Trained physics and maths teachers (trained at three years higher than the level they teach) and appropriate infrastructure/resources; links between universities and school teachers to aid in the delivery and syllabus; programs to make students aware of the relevance and applications of physics and career opportunities in physics
Higher education	Students who are appropriately qualified wanting to study physics in Australia; encourage related disciplines to source physics service teaching from physicists; inducements to encourage excellent and inspiring physics teaching
Research	Vibrant research community that generates new ideas; continuation of schemes rewarding research excellence (centres of excellence, fellowships and international linkage); support for research infrastructure and resources to attract research talent; predictability of funding to attract and retain talent and take research risks that don't depend on short-term funding cycles
Funders	Return on investment (relative to other investment options)
Government	Improved productivity/economic wealth, employment, competitiveness attributed to funding; improved international status; improved national capabilities and expertise
Industry	Access to IP that improves competitiveness and profitability; trained future employees; access to research assets that they wouldn't buy themselves/contract research capacity; favourable conditions for operations in the country
General public	Knowledge to better participate in current debates; benefit of applied IP (to society); education for their children; understanding of the Universe (origin, evolution and fate!)
International community	Access to expertise, collaboration, leverage of their capabilities; ability to address bigger questions that can't be solved in isolation; access to high-quality education and research training

KEEPING A SECRET THE QUANTUM WAY

QuintessenceLabs, building on research at the Australian National University, is the first company in the world to exploit quantum cryptographic technology based on bright laser beams. This enables unbreakable, secure storage and communication of sensitive information through the generation of an ultra-secure cryptographic key. Harnessing proven science, QuintessenceLabs protects communications with real-time, ultra-secure encryption and safeguards critical data with state-of-the-art enterprise security services. An innovative four-layer technology architecture mitigates the risk of data security breach while ensuring regulatory compliance and unyielding public trust with best-in-class data encryption services.

The breakthrough technology of QuintessenceLabs draws on innovative scientific research conducted in Australia in the field of quantum optics. Rather than encoding secret key material using a single photon at a time, a truly random secret key is directly encoded onto a continuous beam of laser light, comprising billions of photons per second. Unlike first generation, single-photon technology which requires complex and expensive photon-emitting and photon-detection components, QuintessenceLabs' technology is able to leverage commercial off-the-shelf telecommunications components allowing for robust design adaptable to a range of operating conditions. Employing broadband encoding and dense wavelength division multiplexing, the technology delivers high performance, cost-effective systems that support provably-secure true one time pad encryption.

Headquartered in the Australian Capital Territory, QuintessenceLabs is now entering the commercial market and aims to be a global leader in the protection of valuable information assets. The company has won a number of awards for its technology and market potential. In 2011 it won the Australian Computer Society (Canberra) ICT Innovation Award and the Australian Capital Territory Chief Minister's Emerging Exporter Award. The company was also winner of the 2012 IBM Asia Smart Camp competition.

See **www.quintessencelabs.com/**

IMAGE: WWW.ISTOCKPHOTO.COM/PETROVICH9

'But these people make the world in their fashion and I in its own. I have not put in the hills and the valleys, and the other stars in the heavens if first I have not seen them, but you have indeed made Jupiter incorruptible without having seen it such.' Galileo, Opere vol II, part 2, page 436 translated from the 17th century Italian original by Charles Donovan, August 2010.

option is for the National Committee for Physics to become responsible for implementation of the plan. Further discussion appears in the 'Conclusions' section of this report.

Today: the impact of physics

The impact of discoveries in physics on our society is broad and profound and goes well beyond the confines of its discipline boundaries. A deep understanding of the forces that shape our environment provides insights into our cosmic origins and has delivered new technologies that have revolutionised many aspects of our daily lives, including communication, information storage, and medical imaging.

The 21st century promises extraordinary advances in our understanding of fundamental questions in physics and the application of physics to improving our society. Such contributions of physics to our world have been ongoing since Galileo overturned the established order of his time and demonstrated the extraordinary power of direct observation of nature.

Exotic partners of the Higgs boson — room temperature superconductors, dark matter, more precise climate models, quantum coherence in room temperature processes, the reconciliation of quantum mechanics and general relativity, efficient ways to transform energy, and sleek devices to interface with the human body — these and more lie just beyond our reach. The success of physics generates constant excitement and anticipation for the next major discovery that will extend the boundaries of our knowledge.

Physics in Australia is funded and managed in a variety of ways. Physics research takes place in universities, government agencies and industry, and is funded by the federal government (both directly, and via the Australian Research Council or ARC), state governments, industrial partners and overseas research organisations. Organisations and agencies such as the Department of Industry, Innovation, Science, Research and Tertiary Education (DIISRTE), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the National Measurement Institute (NMI), the Australian Nuclear Science and Technology Organisation (ANSTO), and the Defence Science and Technology Organisation (DSTO), have distinct roles in performing and supporting physics research and being authoritative custodians of physics knowledge. These structures all have a crucial part to play in exploiting opportunities for the future in Australia.

The future: three opportunity areas in physics

Three broad areas of opportunity for physics emerged from interviews with representatives of the Australian physics community (see *Physics decadal plan 2012–2021, Part 2*) along with their global partners in the international physics endeavour. These are:

- the new quantum revolution
- the quest for new physics and new symmetries
- physics and the society in which we live.

Each of these opportunity areas encompasses a broad range of activities.

1. THE NEW QUANTUM REVOLUTION

Quantum mechanics is one of the most successful theories ever formulated for describing the physical world around us. Most of the revolutionary new technologies introduced in the second half of the last century were based on the quantum revolution which opened the way to the development of semiconductor transistors, lasers, giant magneto resistance (GMR) and new technologies based on the spin of subatomic particles. GMR moved remarkably rapidly from the laboratory, recognised via the 2007 Nobel Prize, into ultra-high capacity disk drives [2]. Mobile phones and the internet, our principal mechanisms for communication today, are also products of our understanding of nature on the atomic and subatomic scales provided by quantum mechanics.

Two promising candidates for this revolution are the quantum computer — a device that can provide an exponential scale-up of computing power — and quantum cryptography — a method of communication that guarantees absolute security.

The development of a quantum computer is widely recognised as one of the ten major challenges confronting science and engineering in the 21st century, and the international race to construct such a computer is of the highest technological calibre. Quantum cryptography, or more precisely quantum key distribution, is a new paradigm in data encryption. While most modern advanced encryption protocols use mathematical complexity for ensuring information security, the advent of a quantum computer, or the invention of a more efficient mathematical algorithm, may render many such encryption protocols insecure. In contrast, quantum cryptography relies on the laws of physics for its information security. As such, an ideal quantum cryptographic system is unbreakable, leading to absolute information security.

The 21st century is already delivering a second wave of the quantum technological revolution in which our understanding of nature at the most fundamental level can again provide unprecedented benefits to society. Significant research effort is now being

2 en.wikipedia.org/wiki/Giant_magnetoresistance

applied to the exploitation of the full spectrum of quantum behaviour in systems both for fundamental science and emergent technologies. Fragile quantum phenomena such as entanglement and coherence have significant potential for new information technology applications.

Australian quantum science enjoys a strong international reputation and engages in research into fields including semiconductors, neutral atoms, ion traps, superconducting circuits, opto-mechanics, photons and quantum dots. The continuation of funding programs based on research excellence (centres of excellence, fellowships, and infrastructure support schemes) is needed to ensure this reputation is maintained and enhanced. In addition, strong engagement with the international research community through co-funded international grant schemes (NSF, EU, etc.), increased numbers of international PhD scholarships, and schemes to allow the exchange of researchers, is also essential to maintain our competitive edge.

2. THE QUEST FOR NEW PHYSICS AND NEW SYMMETRIES

In the first half of the 20th century, the electron and photon were the domain of fundamental physics, but now form the basis of multi-trillion-dollar industries in electronics, communications, computing and photonics.

Through their remarkable convergence, as well as their individual strengths, studies of the physics of the extremely small and the extremely large — at the scale of the particles that form the most fundamental building blocks of matter, and of the large structures which form the Universe — show enormous potential for similar revolutionary breakthroughs in the 21st century.

The advent of floods of experimental data from the Large Hadron Collider and the Square Kilometre Array will bring us closer to understanding the origins of mass, the unification of the fundamental forces, and solutions to the intriguing problems of the nature of dark matter and the expansion of the Universe.

The role of some of the most elegant theories suggesting new symmetries and dimensions will become clearer. The properties of matter and energy under extreme conditions will be measured in colliders on Earth and in the remote laboratories of neutron stars revealed by the observation of gravity waves.

Research excellence schemes and mechanisms to allow Australia and Australians to continue to be engaged in this international quest for new physics and subsequent spinoffs are essential if we are to be seen as contributing to an exciting technological future.

3. PHYSICS AND THE SOCIETY IN WHICH WE LIVE

New materials, constructed by applying unprecedented physical control, can help us cope with climate change, generate energy, improve our health, and sense the world around us.

There will be rapidly increasing opportunities in the next decade to harness outputs from physics to serve our society. Examples include generating electricity with minimal environmental impact, advanced tools for medical imaging, diagnosis and therapy, and informing government decision making on issues of long-term and global significance.

Just as Faraday and Maxwell ushered in an industrial revolution so profound and all pervasive that it is impossible to imagine everyday life before electricity, so the quest for low carbon sources of power promises a similar revolution.

Assessing and addressing the challenge of climate change as the 21st century unfolds will require sound physics and the collaboration of teams with expertise across the innovation continuum, including the discovery of new materials and processes. With regard to energy, while low carbon emission sources of power are becoming more substantial, they still remain stubbornly minor in proportion to demand.

We can anticipate revolutionary physics-based discoveries in the field of energy storage and power conversion and perhaps, if climate change triggers a substantial crisis, the development of radical mitigation strategies. Demands for power efficiency and more accurate climate models will continue to rise.

In the long term, generating electricity from controlled thermonuclear sources presents formidable challenges that will require a deep and prolonged effort from global consortia of physicists and engineers.

The eternal quest to improve health and diagnose disease has been a constant driver in the development of new imaging technologies, most of which have their origin in fundamental physics research.

The medical physics community in Australia makes substantial contributions at both the national and international levels to radiation therapy and oncology, medical imaging, nuclear medicine, nano-dosimetry and radiobiology, as well as to the development of medical devices such as the internationally renowned cochlear implant. Bionic vision is a near-term goal that will be made possible through advances in information processing and the machine–human interface.

The promise of revolutionary lab-on-a-chip technologies is likely to incorporate radical new fabrication technologies exploiting physics at the boundaries with chemistry and engineering. Even more exciting is the potential for the incorporation of artificial devices within the body to enhance degraded functions, perhaps with built-in internal energy harvesting systems to provide the necessary power.

Close collaboration between multidisciplinary teams will be required to meet these challenges.

Four critical areas to securing the role of physics in underpinning Australia's future

Physics allows us to understand the fundamental processes governing our Universe and drives innovation that improves our lives. People who study and understand physics contribute to society in a myriad of ways both within and outside the discipline.

Australia has long been the beneficiary of innovation propelled by the Australian physics community. This decadal plan strives to secure this role of physics in underpinning Australia's future.

The physics decadal plan reviews the current position of physics in Australia, and identifies future directions and opportunities for Australian physics in the global context.

It addresses these issues by making recommendations in four main areas based on data collected in the process of formulation of the decadal plan:

- achieving a physics-literate workforce and community
- realising human capital in physics
- building on physics research and investment
- engaging in the international enterprise of physics.

These critical issues are addressed in the main body of this report.

The scope of physics and the national context

The endeavour to answer the big questions in physics is not the provenance of a single country, and physicists working in Australia are extremely well connected and integrated with the international community. Physics spans cultures and continents, facilitated by global communication and transport networks made possible by the work of earlier generations of physicists. These global networks link Australian physicists and their students and staff with research groups and laboratories around the world. Physicists based overseas come to Australia to work and participate in national programs, to conduct joint research with national centres and to gain access to major Australian infrastructure including the Synchrotron, the Open Pool Australian Lightwater (OPAL) reactor and National Collaborative Research Infrastructure Strategy (NCRIS) facilities such as the Australian National Fabrication Facility, to name a few.

Innovation is central to the advancement of physics knowledge and applications (figure 1). Dr Richard Caro has introduced the concept of an 'innovation continuum' which shows the scope of physics from

Figure 1: The physics innovation matrix.
Dots are indicative of major focuses and are not prescriptive.

	Basic Physics Research	Directed Physics Research	Product Research	Product Development	Market
University	•	•	•		
Centre of Excellence	•	•			
CRC		•	•	•	•
CSIRO	•	•	•	•	•
ANSTO		•	•		
DSTO	•	•	•	•	
Australian Synchrotron	•	•	•		
Industry		•	•	•	•

Adapted from Dr Richard Caro, Tangible Futures Inc.

ORGANIC HIGH-TECH MATERIALS FOR LIGHT AND POWER

The Centre for Organic Photonics and Electronics (COPE) at the University of Queensland focuses on delivering the next generation of sustainable, high-tech materials and concepts for energy generation, lighting, displays, electronics, sensing and imaging. The centre brings together more than 40 researchers from multiple disciplines including experimental and theoretical physics, chemistry and engineering under one unified, strategic banner. The centre has attracted students and staff from around the globe, and the core philosophy of the centre involves the integration of high quality fundamental science with applied outcomes of high scientific and societal value.

Inaugurated in 2007 as a strategic initiative by the University of Queensland, the centre has established world-class facilities for new material design, synthesis and analysis, and developed an extensive network of global collaborators to build Australia's premier laboratory for organic optoelectronic device fabrication and testing. In the last four years staff at the centre have published 120+ papers in top international journals, raised more than $10 million in operational funding and established COPE as one of the world's leading research and technology centres in the field. The centre has produced patents and several early-stage start-up companies, and has grants and research/technology development relationships with a number of companies, particularly in the solar energy and national security sectors. Members of the centre provide policy advice to the state government in renewable energy, and contribute to a number of national science and technology agendas including the Solar Flagships Program and Academy of Science initiatives.

COPE's competitive advantage stems from an integrated approach — physics, chemistry and engineering brought to bear to deliver fundamental and applied outcomes in critical areas of science and technology. This vision is underpinned by significant strategic support from the University of Queensland and the Queensland Government Smart State Strategy, in addition to substantial Australian Research Council and Australian Solar Institute funding, enabling COPE to attract the best international researchers and students to fully utilise the strategic infrastructure investment. Notable scientific and technological achievements include the development of unique sensing materials to detect minute levels of explosives, the demonstration of record efficiencies for large area next generation solar cells, the development of new bio-compatible materials for interfacing biological materials with conventional electronics (bio-electronics), and the creation of new molecular concepts in organic semiconductors. Understanding the physics of the new 'organic semiconductors' is absolutely central to the next materials revolution, just as fundamental physics underpinned developments in the 1960s which delivered the Silicon Age.

See **physics.uq.edu.au/cope**

the 'discovery' end of the continuum of blue-sky curiosity-driven research to the 'applications' end where directed research addresses near-term goals. Physics discoveries have a distinguished record of moving along the continuum on timescales from months to decades. Some of the most important developments in physics, including quantum mechanics and general relativity, have taken more than 80 years to trigger the technological revolutions in our society that we see today.

Economic modelling of the influence of science and innovation on the wealth of nations has shown a link between the strength of the national innovation system of a country and its wealth measured by the gross domestic product (GDP). For example, a triple correlation between the number of patents, the number of publications and GDP was well established for the 20th century and detailed models show the causal link between these indicators [3]. This is a guiding principle for strong emerging economies such as Brazil. In addition, investments in national innovation systems have proven to be of high value in the post global financial crisis period. In this

3 Modelling economic growth fuelled by science and technology, A. Bernades, R. Ruiz, L. Ribeiro, E. Motta e Albuquerque (2006)

period, Australia has made strong investments in education and to some degree in science [4].

Public support for science and innovation, including physics, has provided widespread and important benefits for Australians. Spin-offs arising from the development of basic knowledge and capabilities or the diffusion of new ideas lead to benefits beyond the original expectations of the innovator. The Productivity Commission report *Public support for science and innovation 2007* [5] shows that this public support leads to better government services for education, defence, social welfare and health services. The role of these spin-offs from physics has been recognised for more than a century, and JJ Thomson cited the development of medical x-ray imaging as having arisen from curiosity-driven fundamental research on the nature of electricity [6]. Practitioners of general relativity, once described as 'magnificent cultural ornaments' by Lord Martin Rees [7], laid the foundations of multi-billion dollars' worth of commerce through applications of the global positioning system (GPS). In his book *Symmetry and the beautiful Universe*, Nobel Laureate Leon Lederman estimates that '*today, quantum mechanics and the understanding it brings of the electron, the atom, and light accounts for a major fraction of the US gross domestic product*'. In Australia, the development of the atomic absorption spectrophotometer was said by its inventor, Sir Alan Walsh, to have 'originated in a laboratory devoted primarily to basic, curiosity-oriented research and finished in applied research of tremendous economic value all around the world' [8]. Engineers rising to the challenge of improving radioastronomy images and reducing interference on radio networks developed the core technology for wireless LAN now deployed worldwide [9].

There is no question that Australia's contribution to the physical sciences over the last two decades has been outstanding. In fact, our most recently awarded Nobel Laureate is the physicist Professor Brian Schmidt from the Australian National University (ANU). The 2011 Nobel Prize for physics [10] recognised the discovery by Professor Schmidt and his colleagues that the Universe is expanding at an accelerating rate. It is the first time in almost 100 years that an Australian physicist has received this award, and is an excellent demonstration of the healthy environment for physics in Australia and its strong engagement with the international community.

'My general attitude to research was greatly influenced by the fact that I studied physics at Manchester University. The physics department had an illustrious record of major achievements, including Rutherford's development of the nuclear theory of the atom, Bohr's first theory of the origin of atomic spectra, Moseley's law of X-ray spectra, and [Lawrence] Bragg's work on the determination of crystal structures by X-ray crystallography. A feature of all these advances was [that] whilst they were profound they were all very simple. I think by the time I had finished my course at Manchester I took it for granted that the very essence of a significant contribution to physics was a fundamental simplicity.' A Walsh, 'The development of the atomic absorption spectrophotometer', Spectrochim. Acta B, 54 (1999): 1943–52, reproduced from a draft of a manuscript written in June 1976.

Australian physics has unique challenges in pushing discoveries along the continuum. As the innovation report commented:

> *'The size and structure of our economy and our distance from international markets present Australia with unique innovation challenges and opportunities. The bulk of the knowledge we rely on is generated abroad, so it is essential that we have the absorptive capacity — the skills and international connections — to identify and adapt the knowledge needed to move Australian industries up the value chain as competition at the low end intensifies.'*

It has also been observed by Prof Robin Batterham (President of the Australian Academy of Technological Sciences and Engineering 2008–12), speaking in the context of innovation in the Australian mining industry, that profit margins associated with extraction and processing of minerals plunge with increasing distance from the mine. The margins only increase again when the materials are transformed into a consumer product. While Australia has been highly innovative at the efficient extraction and shipping of raw materials, there has been less success in capturing returns from the highly profitable second peak in the profit

4 Macro-economic effects of the fiscal stimulus measures in Austria, F Breuss, S Kaniovski and M Schratzenstaller *WIFO quarterly* 14 (2009) pa. 214. ideas.repec.org/a/wfo/wquart/y2009i4p205-216.html

5 www.pc.gov.au/projects/study/science/docs/finalreport

6 JJ Thomson, speech to the Conjoint Board of Scientific Studies, 1916. Cited in GP Thomson, *J.J. Thomson and the Cavendish Laboratory in his day*, New York, Doubleday, 1965. B McKellar, private communication

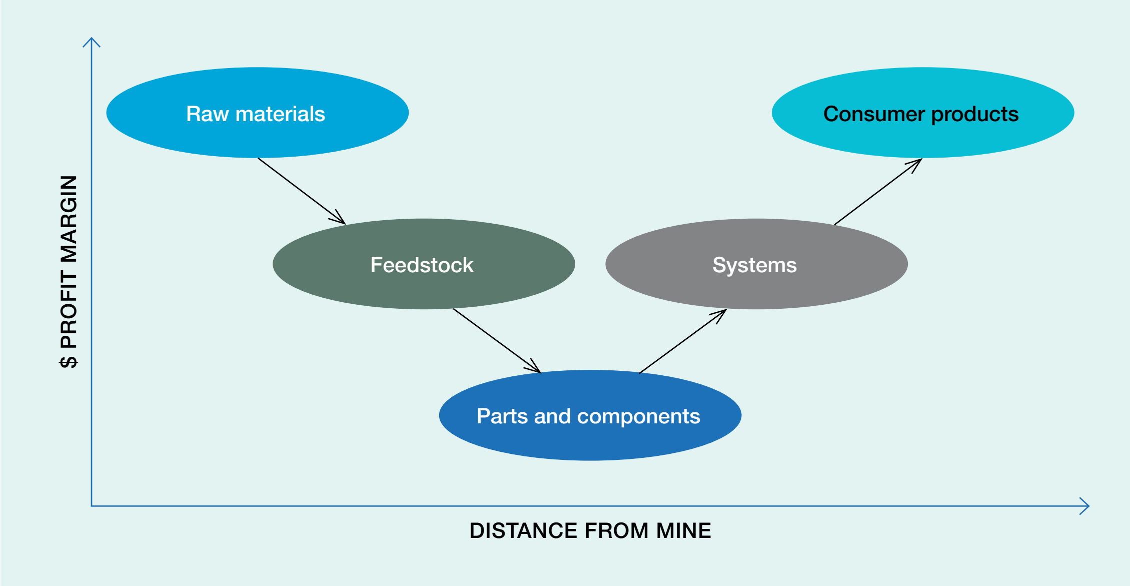
7 www.simonsingh.net/media/articles/Maths-and-science/interview-with-sir-martin-rees/

8 www.science.org.au/fellows/memoirs/walsh2.html

9 www.csiro.au/en/Outcomes/ICT-and-Services/People-and-businesses/wireless-LANs.aspx

10 www.nobelprize.org/nobel_prizes/physics/laureates/2011/

Figure 2: The context of innovation in the Australian mining industry



margins. The second peak presents opportunities for Australian physics.

The 2010 Excellence in Research for Australia (ERA) assessment exercise demonstrated that research in physics is a national strength. This is in part attributable to support from the funding agencies including the ARC. On release of the ERA report in January 2011, the Minister for Science reported that Australia's performance in quantum physics was 'truly outstanding' [11]. Research strength in physics also contributes substantially to the global rankings of Australian universities. The 2012 Academic Ranking of World Universities (ARWU) [12] put one Australian university (ANU) in the top 50 universities in the world for physics, and three in the top 100 (ANU, Melbourne and Swinburne). In the 2012–13 *Times* 'Higher Education rankings for Physical Sciences', two Australian universities (Melbourne and ANU) were ranked in the top 50 in the world.

With regard to ARWU rankings [13], Canada has two universities in the top 50 universities in the world (Toronto and British Columbia), and Australia has none. This is a very significant anomaly in the Australian tertiary education sector when compared to Canada, a country with a similar cultural heritage to Australia. Both Toronto and British Columbia have physics departments with about three times more continuing staff than the largest physics departments in Australia. How our peers in Canada operate warrants a closer examination. Moving one or more Australian universities into the top 50 would be a worthy goal. Highly ranked physics departments are an essential step towards this goal.

Government policy in Australia, as Marginson points out, has focused on equitable outcomes linked to student numbers, and consequently has failed to drive new research capacity that can challenge our Canadian peers [14]. Marginson goes on to point out that a double solution to building capacity at the peak institutions while supporting more general capacity is required but this cannot come from the sector itself. It is essential that the excellent foundations demonstrated by the 2010 ERA process provide a pathway for building our university physics schools to numbers commensurate with our international competitors. This will allow the development of stronger international programs in physics and associated rich programs of advanced teaching and community outreach already seen, for example, in our Canadian peers.

11 Senator Carr's ERA launch speech 'Impressive scorecard for Australian research, 31 Jan 2011' archive.innovation.gov.au/ministersarchive2011/Carr/MediaReleases/Pages/IMPRESSIVESCORECARDFORAUSSIERESEARCH.html

12 www.shanghairanking.com/SubjectPhysics2012.html

13 www.arwu.org/

14 SM Marginson, 'The research capacity dilemma', *The Age* 'Higher Education Section', 29 June 2011

NEUTRONS FROM OPAL FOR ANALYSING INDUSTRIAL MATERIALS AND MAKING MEDICAL ISOTOPES

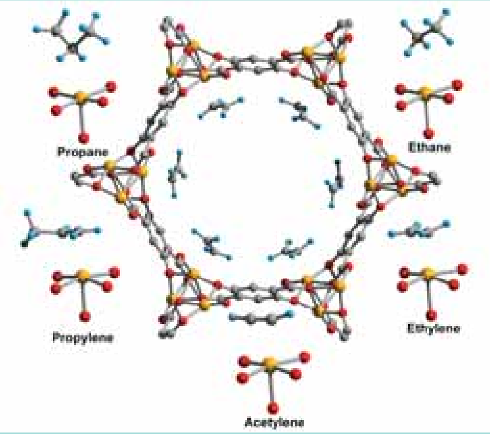
The OPAL Research Reactor in Sydney and its sister facility, the Australian Synchrotron in Melbourne, represent the greatest investment in scientific infrastructure in Australia's history. At present, each is instrumented at roughly 25 per cent of full capacity, having come on line in 2007. Neutron-scattering facilities at OPAL offer a unique ability to penetrate deep into materials or devices, to study magnetism without the effects of electronic charge, and to observe light atoms in the presence of heavier ones. This is particularly important in the case of hydrogen, for which its heavier isotope deuterium can be systematically substituted, giving contrast that cannot be obtained by any other method.

Key applications are:

- measurement and characterisation of stresses in industrial components like welds, aero-engine components and coatings
- understanding nanostructures and helping to improve their manufacture, processing or use
- understanding the way light atoms like hydrogen and lithium behave in important energy devices like lithium-ion batteries, fuel cells and hydrogen storage media, and in energy-intensive activities such as oil/gas extraction
- contributing to grand challenges in physics, including the identification of the mechanism of high-temperature superconductivity and other exotic quantum states of matter.

In addition to OPAL's role as a bright neutron source for physics and the other sciences, it also plays an important role in producing technetium-99 for most of Australia's nuclear medicine, and has a major commercial role in producing high-quality phosphorus-doped silicon for the global semiconductor industry.

See **www.ansto.gov.au/research/bragg_institute**



IMAGES: NIST / ANSTO

The first image is from *Science* 335(6076), 1606-1610 (2012), and is potentially important as a way to separate gases within natural gas streams without having to resort to energy-intensive liquefaction methods. It is part of a collaboration between UC-Berkeley, the National Institute of Standards and Technology and ANSTO.

INTRODUCTION

HIGH PRECISION TESTS OF TIME, SPACE AND GRAVITY

One of the ongoing quests in fundamental physics is the search for a theory to explain all the fundamental constants and to unify the two most successful but apparently incompatible theories of physics, namely general relativity and quantum mechanics. Potential unification attempts have been linked to spontaneous breaking of Lorentz invariance and the possible variation of fundamental 'constants'. It is predicted that such violations will occur at the Planck scale, well beyond the reach of existing particle-accelerator experiments. An alternative to accelerator experiments is to undertake precision measurements at low energy, where Planck scale effects are suppressed but still in principle measurable.

Eleven years ago the University of Western Australia's Frequency Standards and Metrology group began using their world record beating ultra low noise cryogenic sapphire resonators and oscillators to test rigorous theoretical calculations of the sensitivity of this technology to Lorentz violating electrodynamics (such as a non-constant speed of light) and putative variations of fundamental constants.

The group published these proposals in 2003 and obtained Australian Research Council funding and fellowships to realise these experiments. Together with international collaborators the group has performed a range of tests of the foundations of physics, improving on previous tests and placing constraints on possible theories of quantum gravity. The group has also been involved in the Atomic Clock Ensemble in Space mission, an exciting international mission funded by the European Space Agency that will test the foundations of physics by comparing the world's best clocks in space to the world's best clocks on earth.

See **www.fsm.physics.uwa.edu.au/** and **equs.org**

Critical issue 1: achieving a physics-literate workforce and community

Addressing the need to improve teaching of physics at all school levels is a fundamental requirement for achieving a physics-informed government, workforce and community. To ensure a steady supply of physicists in the immediate future, there is a need to improve the recognition of the contribution made by teachers in nurturing a passion for physics in the next generations. It is essential that physics be taught by well-trained and enthusiastic teachers properly supported with the resources needed to do their job.

A focus on teaching physics topics in primary school and the early middle school years is also required to reverse the current trend of lower performance of girls in physics and mathematics.

Invigoration of primary and secondary school sector physics education, combined with appropriate mathematics education, will magnify the competency and motivation of school students to study physics at tertiary level. This in turn will to lead to higher availability of skilled graduates for the higher education and research sector, industry, business and government.

As pointed out in the 2006 audit of science, engineering and technology skills, '*Australia's productivity and success in the highly competitive global market is increasingly reliant on science, engineering and technology (SET) skills. Our abilities in research and development, innovation and discovery are dependent upon the availability of suitably skilled scientists and engineers.*' [1]

Innovation from this community can be a driver of economic growth as the products of physics research are incorporated into the economy.

Improved science literacy in the general public and a more highly skilled workforce are further benefits of improved physics school education. Effective outreach programs by universities and research organisations can also successfully raise the community's awareness of physics.

As the 21st century unfolds, there continue to be significant challenges in ensuring that physics informs important decisions made by our government. We need to be vigilant to help governments avoid making decisions involving significant expenditure, if sound physics can foresee that these decisions would have poor or unintended outcomes.

It is critical that the established and robust evidence base in physics inform an urgent and comprehensive analysis by government of alternative power sources available to meet our national and global energy needs.

DECADAL OBJECTIVES

- attract and retain students in physics at all educational levels
- increase the quality and number of appropriately qualified physics teachers across the school sector
- reduce the gender differential in physics competency at all school levels
- improve physics-literacy amongst the lay community
- improve the use of the physics evidence base to inform policy development

RECOMMENDED ACTIONS AND PATHWAYS

a) Quality teaching — quality students

- Establish a bonded scholarship scheme to encourage excellent physics graduates into a secondary education teaching career.

A bonded scholarship scheme could be modelled after the Medical Rural Bonded Scholarship Scheme (www.health.gov.au/mrbscholarships). One hundred additional Commonwealth-supported places each year could be offered to first year Australian physics students at participating universities across the country. Students accepting the scholarship would commit to working for several continuous years as a physics teacher after completing their teacher training. The scholarship should be worth more than $25 000 a year, be tax free and indexed annually.

1 http://bit.ly/WiTK1L

- Ensure the physics component of the national curriculum is founded on rigorous analytical and quantitative reasoning, and encompasses the fundamentals of physics, as well as their applications in today's life.
- Introduce a mandatory requirement that secondary school teachers are trained in physics to three years above the highest level at which they are required to teach physics. This corresponds to first year university physics for years 7–10 teachers and a major in physics for years 11–12 teachers.
- Endorse an undergraduate science degree together with a teaching qualification as the preferred qualification option for years 7–12 physics teachers.
- Require science education training as an integral part of the teacher training for future primary school teachers.
- Resource universities to provide programs that up-skill and update school physics teachers as part of their professional development.
- Introduce options for science, mathematics and physics teachers to allow them to study part-time for a teaching MSc.
- Continue ongoing support for the development and implementation of the Australian Academy of Science's primary school program *Primary Connections* and its junior secondary school program *Science by Doing*; these are award-winning approaches to professional learning and school curriculum resources which have been shown to have a positive impact on the quality and quantity of science taught in schools.
- Encourage school programs like *Scientists in Schools*, *STELR* [2], *Science and Engineering Challenge* [3] and *SPICE* that promote contemporary quality school science learning.
- Reward excellence in physics teaching. A panel of leading teachers should be convened to identify the best process, perhaps under the auspices of the Australian Institute of Physics (AIP) Education Convener.
- Introduce teaching bursaries to support students interested in teaching physics to gain qualifications.
- Start public campaigns to raise the status of teaching as a profession, modelled on the successful Victorian State Government campaign.
- Establish a joint-academies taskforce to harness the strengths of e-learning in tertiary institutions with a view to developing the next generation of teaching technologies jointly across the sector. This will include the establishment of a competitive teaching and learning scheme to aid in the transformation of education in science, technology, engineering and mathematics (STEM) and the development of metrics to evaluate STEM education.
- Identify and address the underlying causes of the under-representation of girls in physics at all levels of school education.
- Promote the spectrum of available career paths to students to enable them to make informed decisions about career choices.
- Provide career advisory services particularly for school students (but also university undergraduates and graduates) so they can make informed choices about future career pathways, such as teaching, research, government or industry employment.
- Aim to have at least one or more Australian universities in the top 50 universities of the world by attracting the best and brightest students to physics schools.

b) Internationally competitive Australian physics undergraduate and postgraduate students

- Broker agreements between Australian higher education providers to ensure that the Australian physics PhD is comparable in breadth, depth and duration of training to those in the USA and the European Union (EU); particularly by providing resources for the inclusion of postgraduate coursework as a key component for higher degree by research training.
- Merge the Australian postgraduate award (APA) scholarship scheme with the international postgraduate research scholarship (IPRS) scheme to open up the combined APA/IPRS scholarship pool to all domestic and international students.
- Provide a balance of learning experiences between theoretical, experimental, observational and computational physics to ensure 'employment readiness' of graduates not only for research but also for industry and business.

c) Valuing and promoting physics

- Commit resources from the higher education and research sectors to support high-quality outreach programs with long-term impact that can reach and engage Australians.

2 http://stelr.org.au

3 www.newcastle.edu.au/faculty/engineering/community-engagement/challenge/

- Develop programs and commit resources to promote the value of physics and physics education and careers to school students, parents, industry, universities and government bodies.
- Ensure the National Mathematics and Science Education and Industry Adviser located within the Office of the Chief Scientist works with the physics community to address physics-specific challenges.

The challenge of physics education

Our wider society expects that education will provide the knowledge and basic skills for people required to operate in a society in which technology is created and in which they will find employment. There is an opportunity for increasing the general physics awareness of the community through raising the standard of physics education in schools. Furthermore, our society expects that the advances in technology to which we have all become accustomed will continue at an ever-expanding rate. The development and effective application of these advances can only occur with reference to guiding principles based on a firm foundation by well-educated decision makers serving a well-educated and informed community.

School physics education is expected to provide students with the skills needed in their working lives, for entering tertiary education and for providing

POWERING AHEAD TO A GLOBAL ENERGY SOLUTION: FUSION POWER RESEARCH IN AUSTRALIA

Fusion, the process that powers the sun and the stars, promises millions of years of safe, non-greenhouse-gas emitting base-load power. Progress towards realising fusion power research has outstripped the rise in speed of computers, and the proof-of-principle experiment, the International Thermonuclear Experimental Reactor (ITER), is now under construction. ITER, one of the world's largest science experiments, is supported by a consortium of governments representing over three billion people. The Australian ITER Forum and its institutional partners represent the Australian fusion science community in international forums.

The ANU is the hub of Australia's involvement in fusion research as host of the Australian Plasma Fusion Research Facility, which supports Australia's only plasma fusion confinement experiment, the H-1 heliac, and a new materials facility, the materials diagnostic facility. These build on an international reputation in plasma science, theory and modelling. ANU also spearheads broad international collaborations based on the deployment of novel instrumentation and diagnostic systems, development of MHD theory and associated 3D codes, advanced data-mining techniques, and the application of Bayesian software tools for integrated modelling and data analysis. The ANU has also recently formed a new collaboration with ANSTO to develop and test new materials for the extreme temperatures and highly magnetised environments of fusion plasmas. The University of Newcastle and Sydney complement these research thrusts with the fabrication of new materials capable of coping with extreme environments, and Curtin University has a global profile in modelling the atomic and molecular collisions needed to realise fusion power.

See **prl.anu.edu.au/**

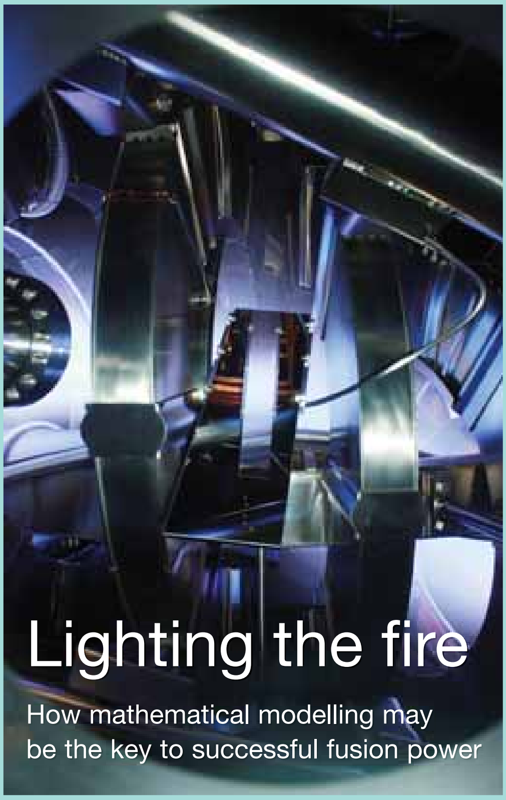


IMAGE: AUSTRALIAN NATIONAL UNIVERSITY

THE SCIENCE AND ENGINEERING CHALLENGE

Science outreach usually has as it goal increasing interest in science. However, there is considerable evidence that students are interested in science but that they see no role for it in their careers or future lives. The key to increasing the number of potential physicists involves three steps: convincing them that a career in physics is interesting, challenging, and rewarding; demonstrate to them that there is a breadth of physics opportunities to study and work on in Australia; and get them enrolled in the relevant degrees to achieve these goals. A national structured program of outreach targeting these three stages is essential to ensure that there will be future opportunities for Australian students to participate in this exciting future. The elements of this program are largely in place with the Science and Engineering Challenge, the National Youth Science Forum and university recruitment and outreach programs.

The Science and Engineering Challenge is a national program which involved over 20 000 year 10 students from 800 high schools in 2011. Its goal is to change misconceptions about careers in science and engineering to demonstrate that they require creativity, innovation, problem solving and teamwork. This succeeds in putting science and engineering in the same exciting light as other careers that students encounter through the modern media and it has succeeded spectacularly in convincing them to continue studying physics, chemistry and mathematics in senior high school to keep career options open. Detailed evaluations of this program have demonstrated the impact not only on the students' choices in senior high school but also on their choice of university degree. The added benefit of this program is the deep engagement of the local community, broadening the appreciation of the consequences of the skills shortage.

Once the interest of students has been raised it is important to reinforce it and that is where the National Youth Science Forum plays a key role. It selects 450 year 11 students from 1400 applicants from around Australia each year for sessions in Canberra and Perth. The forum offers two weeks of exposure to the very best of science on offer using dynamic and eminent scientists convincing students that not only is science an exciting career but that it is within their capability to achieve. The forum cooperates with many industrial partners and highlights the many opportunities that are available for graduates with a science or engineering degree. The forum is regarded by the students as a life-changing experience and gives them valuable contacts to their peers. Analysis over many years shows that the vast majority of the over 8000 attendees have enrolled in and completed science and/or engineering degrees and are successful in a wide variety of careers.

See **www.newcastle.edu.au/faculty/engineering/community-engagement/challenge/** and **www.nysf.edu.au**

IMAGE: UNIVERSITY OF NEWCASTLE

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knowledge that enables them to take full advantage of what our society has to offer. Physics literacy also permits them to take part in debates on questions of common interest such as energy security and climate change.

The greatest opportunities to achieve the overarching goal of a more physics-informed workforce and community and for increasing the number of young school leavers who want to study physics are through the invigoration of primary and secondary school physics education. This will lead to increased competency and motivation of school students to study physics at a tertiary level. This in turn is expected to lead to positive effects from a higher availability of skilled graduates for the higher education and research sector, industry, business and government.

High-quality outreach programs by universities and research organisations can be expected to have a high impact on reaching all Australians and raise their awareness of physics. This has certainly been the experience of the *Science and Engineering Challenge*.

There are several issues that affect the enrolment of students into physics in Australia. Firstly, there is a low level of public awareness of the benefits of physics to society and therefore students show little interest in studying physics, particularly as they do not see how the study of physics can apply to their lives and their future career choices. As well as the general lack of awareness surrounding physics, there are often negative perceptions of physics being too difficult and many students consider physics only as a prerequisite hurdle for entry into other courses. The perception of physics as a difficult subject can arise from the need for studies in physics to be supported by parallel studies in advanced mathematics and the fact that life experiences and common sense typically do not provide useful foundations except in the most general terms. Positive school-age experiences often shape the desire of students to study particular subjects. Therefore, the quality of physics teaching will influence the desire of students to continue studying physics in the final years of school and at university.

These issues are not unique to Australia. Several recent US studies addressed the development of a national framework for K–12 science education and the question of how to recruit more students into tertiary physics programs. The framework for a K–12 science education report [4] produced by a committee of the US National Research Council and chaired by Australian expatriate Professor Helen Quinn from Stanford University, identified three dimensions of science learning:

- scientific and engineering practices
- crosscutting concepts
- disciplinary core ideas.

Further work on the implementation of this framework will develop science standards, teacher preparation, curriculum materials, professional development and teaching resources. With regard to the recruitment issue, this acute problem has been addressed by the SPIN-UP report, *Strategic programs for innovation in undergraduate physics* [5]. This report identified the common factors to multi-year physics departments that were increasing the number of graduates at a time when enrolments were declining overall. These common factors are:

- a supportive, encouraging and challenging environment for both faculty and students characterised by professional and personal interactions among faculty and students
- energetic and sustained departmental leadership focused on a vision of an excellent undergraduate program
- a sense of constant experimentation with and evaluation of the undergraduate physics program to improve physics teaching, undergraduate research, student recruitment and advising.

4 www.nap.edu/openbook.php?record_id=13165&page=R1

5 A report produced jointly by the American Physical Society, American Institute of Physics and American Association of Physics Teachers. www.aps.org/programs/education/undergrad/faculty/spinup/spinup-report.cfm

Figure 3: Percentages of students reaching international benchmarks in year 4 and year 8 science compared to a number of countries that ranked higher than Australia

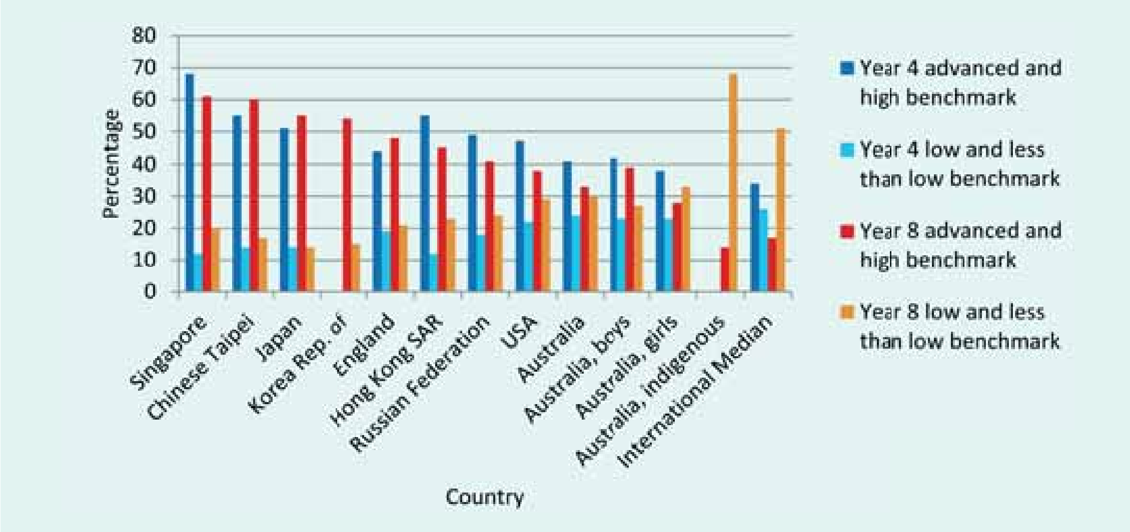
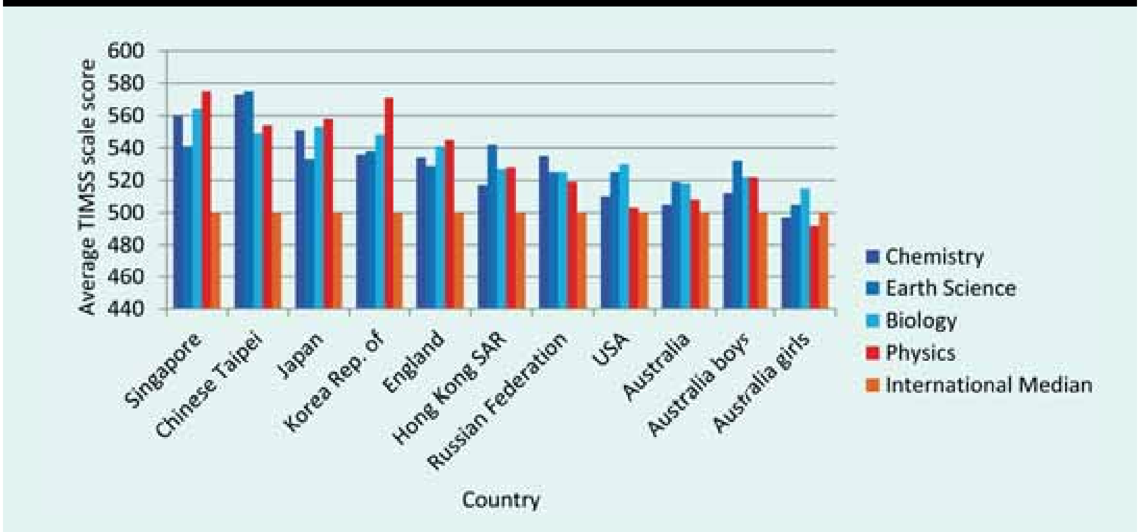


Figure 4: Average TIMSS scale (2007) scores for the four science subjects in year 8



Like the introduction of the Physical Sciences Study Committee [6] which engaged the global physics teaching community five decades ago in curriculum reform, it is possible that a second global endeavour could evolve from these initiatives.

The primary and secondary sectors

Students graduating from the Australian education system can be assessed against international benchmarks by two international assessment vehicles: the Trends in International Mathematics and Science Study (TIMSS) which is repeated every five years and focuses on assessing performance in mathematics, physical, life and earth science at the year 4 (i.e. age 10) and year 8 (i.e. age 14) levels; and the Program for International Student Assessment (PISA) of the Organisation for Economic Co-operation and Development (OECD) which is a comparative assessment of 15-year-olds across the breadth of reading, mathematics and science subjects. TIMSS has a more explicit curriculum focus than PISA, and provides data on subjects that are taught in most countries. These benchmarks have identified that Australian school students are currently performing below international benchmarks in science and mathematics. It is possible that performance will continue to trend downwards relative to our Asian neighbours into the future.

The most recent TIMSS data is from 2007. The study showed that whilst the performance of year 4 students has remained consistent, there has been a decline in the performance in mathematics, physical,

6 www.compadre.org/portal/pssc/pssc.cfm

Figure 5: Percentages of Australian students reaching international benchmarks in year 4 and year 8 mathematics, in comparison with the major Asian neighbours and the international median

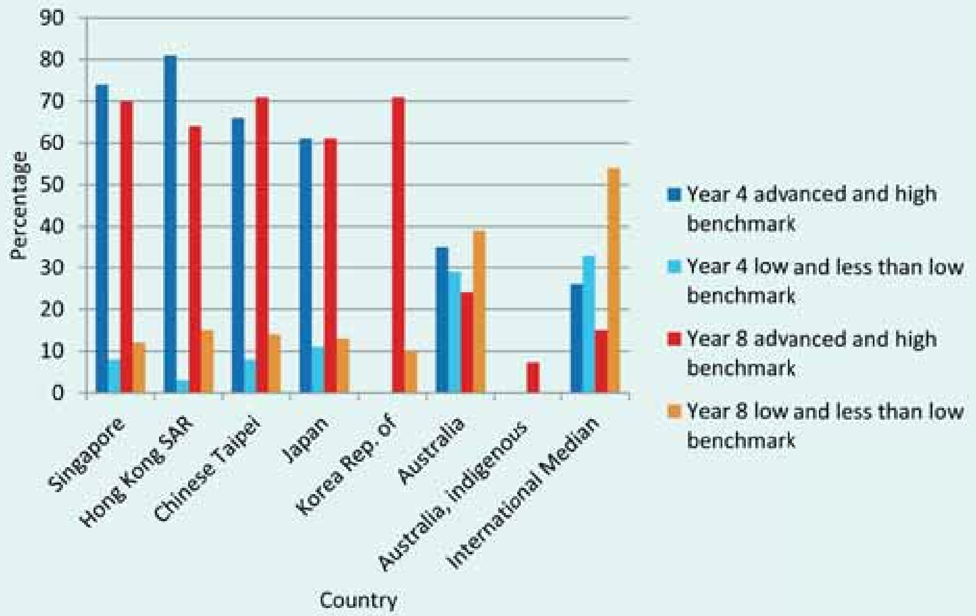
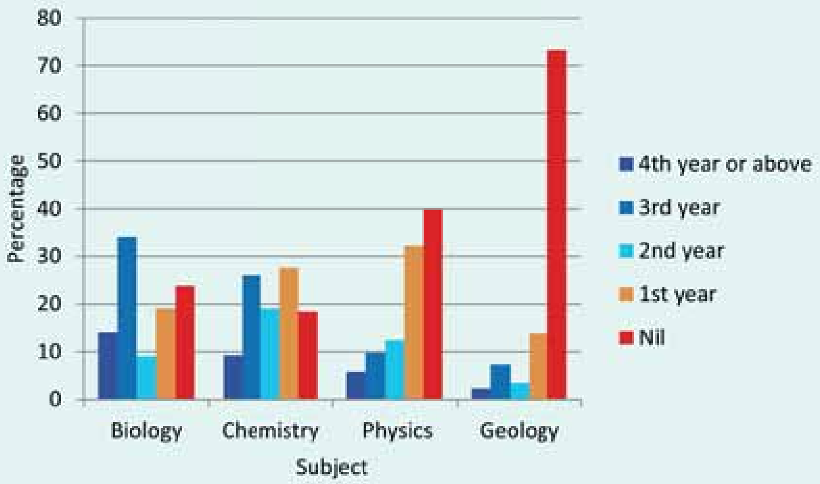


Figure 6: Disciplinary background tertiary education level of middle school science teachers



life and earth sciences at the year 8 level (figure 3). Although Australian year 4 students ranked above the international median, they ranked well below Singapore, Chinese Taipei, the Hong Kong Special Administrative Region, Japan and the Republic of Korea, countries that have emerged as the economic power houses of the Asia–Pacific region, and also below the Russian Federation, England and the USA. Similarly, Australian year 8 students ranked only just above the international median but well below students from its Asian neighbours, the Russian Federation and England. Physics and chemistry were the science disciplines in which Australian students performed least well (figure 4).

In contrast to the international trend for girls to outperform boys [7, 8, 9], in Australia year 8 boys outperformed girls in both mathematics and science; less than a third of girls were at an advanced or high performance standard in science and one third of girls had not met or only just met the low

7 TIMSS 2007 Taking a closer look at mathematics and science in Australia. www.acer.edu.au/documents/TIMSS_2007-ExecutiveSummary.pdf

8 TIMSS 2007: Taking a closer look at mathematics and science in Australia. www.acer.edu.au/documents/TIMSS_2007-AustraliaFullReport.pdf

9 Highlights of TIMSS 2007 from an Australian perspective. www.acer.edu.au/documents/TIMSS_2007-AustraliaHighlights.pdf

performance standard (figure 3). When compared to other countries in which boys outperform girls, Australia only ranks higher than Tunisia, El Salvador, Ghana and Colombia. Also of significant concern in Australia is the markedly poorer performance of Indigenous students, which is a trend that appears to be worsening.

The 2007 TIMSS study showed that a positive attitude towards mathematics and science is correlated to a higher achievement in these subjects. In Australia, students' attitudes towards mathematics and science have declined between year 4 and year 8 both in an absolute sense, and even more dramatically relative to the international average; the positive attitude index of year 8 students towards mathematics has decreased since 1995. The percentage of students achieving international benchmarks in the enabling science of mathematics is also markedly lower than for our major Asian neighbours (figure 5). Equally of concern is the value or relevance that the students place on science as part of their education and life. This is only reported for year 8 students, and while it is close to the international median for mathematics, it is well below the international median for science.

OECD PISA results indicate that Australian 15-year-olds are significantly above the OECD average in all indicators of literacy, numeracy and science literacy; however, the issues highlighted in the TIMSS 2007 study are confirmed [10].

The international benchmarks reveal that the school education sector has a lack of suitably trained science teachers at all levels of the sector. Nearly 43 per cent of senior school (years 10–12) physics teachers lacked a physics major, and one in four had not studied the subject beyond first-year. According to the TIMSS 2007 report, Australia's year 4 students were taught both mathematics and science by teachers significantly less qualified than the international average. Physics was the weakest area in Australia for both year 4 and year 8, in terms of how well prepared teachers felt they were to teach this topic.

A likely explanation for the low ranking for performance in, and attitude toward, studies is the lack of suitably trained science teachers at all levels of this sector (tables 2 and 3). The first real opportunity to introduce potential future scientists to physics is in primary school, but primary school teachers are given little, if any, training in science to facilitate learning. Of equal concern is the lack of effective mathematics teaching, particularly as students who become disengaged with maths before finishing primary school are unlikely to follow education paths to science [11].

Fourteen per cent of science teachers surveyed in a 2006 study by the Australian Council of Deans of Science lacked a minor in any of the four subjects of biology, chemistry, physics and geology. These teachers formed 16 per cent of all teachers of junior school science, 12 per cent of middle school (years 7–9) science teachers and nearly 6 per cent of senior school science teachers.

Nearly 8 per cent of all respondents had not studied any of the four subjects of biology, chemistry, physics and geology at university. These teachers formed 8 per cent of all teachers who taught junior science, 5 per cent of all teachers of middle school science and less than 2 per cent of all teachers of senior school science (figure 6).

In year 8, less than 50 per cent of teachers had a mathematics degree or mathematics education qualification; this is significant as mathematics is considered to be an enabling subject for physics.

These findings may go a long way to explain the poorer performance of the year 4 and year 8 students in the TIMSS 2007 and the PISA 2006 studies in the subjects of physics and earth sciences, and the poorer performance of students in remote areas where younger and less-qualified teachers are employed.

These figures give a complementary perspective to those presented by the Chief Scientist's report [12] which relates solely to senior year teaching qualifications.

Data from the Education Committee of the Victorian AIP [13] suggests that in 2008, a third of the physics teachers will have retired by 2016, and about 50 per cent will have retired by 2023. However, retirement expectations in 2008 are likely to have been modified by the financial crisis that followed 2008. Many teachers comment that their retirement is being delayed to ensure financial security. On the other hand, retirements may come with a rush in a few years time if economic conditions improve or even remain stable.

10 OECD (2011) *Lessons from PISA for the United States*, Strong performers and successful reformers in education, OECD Publishing. dx.doi.org/10.1787/9789264096660-en

11 Maths? Why Not?, Final report prepared for the Department of Education, Employment and Workplace Relations (DEEWR). aamt.edu.au/content/download/8151/104819/.../MaWhNo.pdf

12 www.chiefscientist.gov.au/wp-content/uploads/Office-of-the-Chief-Scientist-MES-Report-8-May-20121.pdf

13 Dan O'Keeffe, private communication

Table 2: Teachers with either none or Year 3 and higher level of tertiary education teaching in field, 2010

	Highest Year Level of Tertiary Education in Field								
	None			Year 3 and higher			Total		
	Metro.	Prov.	Remote	Metro.	Prov.	Remote	Metro.	Prov.	Remote
Year 7–10 Maths	359	223	31	669	266	48	1484	724	119
	24%	31%	26%	45%	37%	40%			
Year 11–12 Maths	112	62	7	600	226	22	943	397	51
	12%	16%	14%	64%	57%	43%			
Year 11–12 Physics	21	11	2	139	66	4	248	120	11
	8%	9%	18%	56%	55%	36%			
Year 11–12 Chemistry	12	7	0	220	103	1	229	145	6
	4%	5%		74%	71%	17%			
Year 11–12 Biology	18	17	2	342	147	14	389	180	18
	5%	9%	11%	88%	82%	78%			

Extract from the Chief Scientist's Report *Mathematics, Engineering and Science in the National Interest*, May 2012

metro metropolitan, *prov* provincial

USING X-RAY CRYSTALLOGRAPHY TO FIGHT INFLUENZA

In a typical Australian winter, around 1500 deaths are attributed to the influenza virus. CSIRO, in collaboration with research partners and industry, has revolutionised the treatment of influenza with drugs of pinpoint precision. This has been a truly multi-disciplinary project. A crucial element has been the use of X-ray crystallography, a key tool from physics that has allowed researchers to identify a region on one of the surface proteins of the flu virus that does not change in any of its strains. Using the methods of rational drug design, this has allowed the design of a drug that 'locks' onto this section of the virus and stops the infection progressing. This approach is now also being used for diabetes, hepatitis and cancer.

From fundamental X-ray physics to crystal structure, this research began in 1978 when Dr Graeme Laver of the Australian National University's John Curtin School of Medical Research in Canberra obtained crystals of one of the crucial surface virus proteins (neuraminidase) for the first time. Next CSIRO's Dr Peter Colman FAA and Dr Jose Varghese produced improved crystals and solved the three-dimensional structure of two influenza neuraminidases with X-ray crystallography. They used amino acid sequence data generated by Dr Colin Ward FAA and his CSIRO colleagues to build the three-dimensional structure from their X-ray crystallography data. With this information they identified and characterised a small unchanging region in the neuraminidase protein that occurs in all strains of influenza. This showed a chink in the virus's armour. A group of scientists led by Professor Mark von Itzstein FAA at the Victorian College of Pharmacy, Monash University, Melbourne, designed and synthesised a special drug that 'locks' onto this section of the virus and prevents it from spreading in the infected patient. In this way the infection is halted.

This collaborative research between CSIRO and the Victorian College of Pharmacy was funded by the Melbourne-based bioTechnology company Biota Holdings Ltd. Biota was floated on the Australian stock exchange to raise funds to conduct this project.

Dr Colman, Professor von Itzstein and Dr Laver shared the 1996 Australia Prize for their contributions to this project.

See **www.csiro.au/en/Outcomes/Health-and-Wellbeing/Treatment/Relenza-and-the-flu-virus.aspx**

The recruitment of new, enthusiastic and well-qualified secondary school physics teachers must be a priority.

There is also an opportunity to address the current gender imbalance that is already evident at the primary and early secondary school level to ensure that adequate numbers of women enter tertiary physics courses and ultimately pursue physics careers.

The higher education sector

Of the 30 universities that offer physics education in Australia, 19 have undergraduate courses accredited by the Australian Institute of Physics. Despite the often fierce competition between Australian universities with regard to attracting the best graduates and postgraduates for research, several of the tertiary institutions also collaborate and complement each other's activities.

Table 3: Percentage of students in year 4 and year 8 taught by teachers with various levels of qualification (by field of post-secondary specialisation) in mathematics or science

Year 4 mathematics teachers	
Primary/elementary education with a major or specialisation in mathematics	7
Primary/elementary education with a major or specialisation in science but not in mathematics	5
Mathematics or science major or specialisation without a major in primary/elementary education	1
Primary/elementary education without a major or specialisation in mathematics or science	84
Other	2
Year 4 science teachers	
Primary/elementary education with a major or specialisation in science	12
Primary/elementary education with a major or specialisation in mathematics but not in science	2
Science or mathematics major or specialisation without a major in primary/elementary education	2
Primary/elementary education without a major or specialisation in science or mathematics	82
Other	2
Percentage of students with teachers qualified by major area of study in their post-secondary education	
Year 8 mathematics teachers	
Education — mathematics	46
Mathematics	49
Education — science	25
Science	34
Education — general	32
Other	39
Year 8 science teachers	
Education — science	63
Biology, physics, chemistry or earth science	85
Education — mathematics	16
Mathematics	22
Education — general	39
Other	30

‘I decided to become a physicist specifically at age 15. I had an amazing physics teacher at school and just decided then that I wanted to study physics... I had previously wanted to be a musician and I was on a music scholarship at school, but at that point I decided I wanted to be a physicist.’ University physics professor

The recent growth in physics undergraduate enrolments has a contribution from growth in the number of international students. Of the approximately 400 individuals who graduate each year with a physics degree, at least one quarter are international students. The higher education sector staffing profile shows a breadth of both teaching and experimental expertise across all sub-disciplines with peaks in astronomy/astrophysics, condensed matter physics and optics and photonics.

The higher education sector is dependent on the availability of high-quality and capable entrants into the university system from schools and therefore is at risk of not being able to produce sufficient numbers of graduates and trained researchers to satisfy the needs of all other stakeholder sectors if the current downward trend in physics education at the school level is not addressed.

The main outputs from the higher education sector are graduates (BSc and BEd) trained in physics, trained researchers (Masters, PhDs, postdocs) and new knowledge delivered as publications, conference papers, books and intellectual property. Students, parents, industry, federal, state and local governments as funders of the sector’s activities, and universities are the key stakeholders of this sector.

Although there is competition within the sector in Australia, there is little differentiation among physics curricula at the undergraduate tertiary education level. However, at the postgraduate research training level there is more diversity, based on the research strengths of each university.

Competition for Australian tertiary institutions increasingly comes from international education providers that perform well in international rankings and can provide lower cost education. However, the main competitor to physics tertiary education is courses from other disciplines e.g. biology, engineering, chemistry, medicine, environmental sciences. Although these disciplines require physics as an enabling science, they increasingly use in-house resources to teach physics, a practice that is exacerbated by student-based funding models which have resulted in a decrease in physics service teaching to other disciplines. This means that the undergraduates in these disciplines are taught less physics than student cohorts a decade ago.

To a large degree, the recent growth in undergraduate physics enrolments has come from growth in the number of international students choosing Australian universities as destinations. Future growth in international student numbers will depend on the international reputation of Australian physics departments which is determined to a large degree by their research excellence and the value delivered relative to the cost of this education.

The gender imbalance that is already evident at the primary and early secondary school level needs to be addressed to ensure that adequate numbers of women enter tertiary physics courses and ultimately pursue physics careers. If the issues of lower confidence and subject matter competence in girls are not addressed, there is a high risk that the gross gender imbalance that is seen in other sectors of the physics community will be perpetuated.

OPPORTUNITIES

Addressing the needs of the physics community to improve teaching of physics at all school levels is seen by the physics community as one of the most important requirements for achieving a physics-informed workforce and community. The most important requirement overall was for a comprehensive and expertly delivered physics curriculum in schools.

One of the challenges in school science generally and physics in particular is that the subject is sometimes not seen as relevant and contemporary by students. Unfortunately for many students physics is perceived as pre-20th century knowledge with little connection to their lives. This is a paradox given the enormous impact of physics on shaping all aspects of contemporary society. The Academy programs *Science by Doing* and *Primary Connections* present physics and science in an exciting contemporary context to which students can relate. As a result of the more active engagement fostered by these programs, there is deeper learning and more positive attitudes.

Invigoration of primary and secondary school sector physics education, combined with appropriate mathematics education, will lead to positive domino effects in terms of increased competency and motivation of school students to study physics at tertiary level. This in turn is expected to lead to positive effects in terms of a higher availability of skilled graduates for the higher education and research sector, industry, business and government.

Students who select other career paths, but are required to take physics classes, will benefit from better physics education at school. This will lead to a more highly skilled workforce in many professions.

A further benefit of improved physics education at the school level will be improved science literacy of the general public as many of the students, who will not study physics at a tertiary level, will have an increased understanding of the potential of physics and physicists to solve important global problems.

The need for teaching physics concepts in a more contemporary manner during the primary and lower secondary school years is important to improve current student interest for both girls and boys.

PROSPECTING WITH GRAVITY

Rio Tinto is funding a major research program in the School of Physics at the University of Western Australia (UWA) for the development of the state-of-the-art VK1 cryogenic airborne gravity gradiometer for minerals exploration. The key IP was a spin-off from work on a resonant bar gravity wave detector at UWA. The VK1 is the most advanced mining exploration Technology developed by Rio Tinto and aims to find 'needle in a haystack' ore bodies.

Operating from an aeroplane, VK1 measures changes, or gradients, in the Earth's gravity field that allow detection of otherwise invisible, buried ore bodies. Some 30 years in the making, VK1 is now in flight trials with Rio Tinto.

The VK1 project is a joint endeavour between Rio Tinto's Exploration and Technology & Innovation teams and UWA. The three groups are pooling their knowledge of ore body geology and advanced physics, as well as their engineering expertise, to make the vision of VK1 concept originator and technical director Dr Frank van Kann a reality.

The project has a number of features that provide an interesting model for industry-university partnership on research that has outcomes directly relevant to industry. Whilst most of the research and technical staff on the project are employed through UWA, project management and oversight is provided via Rio Tinto staff, a number of whom are located at UWA. Whilst making use of infrastructure at UWA (for which there is an infrastructure charge), particularly the workshop, there has been significant co-investment by the School and Rio Tinto in new infrastructure necessary for the project to progress in a timely manner. This infrastructure is available to other researchers in the School, but with priority for the industry partner. The project has also led to the implementation of an industry standard health and safety culture in a university research environment.

See **http://www.riotinto.com/documents/111027_Royal_visit_for_Rio_Tinto_and_The_University_of_Western_Australias_needle_in_a_haystack_exploration_Technology.pdf**

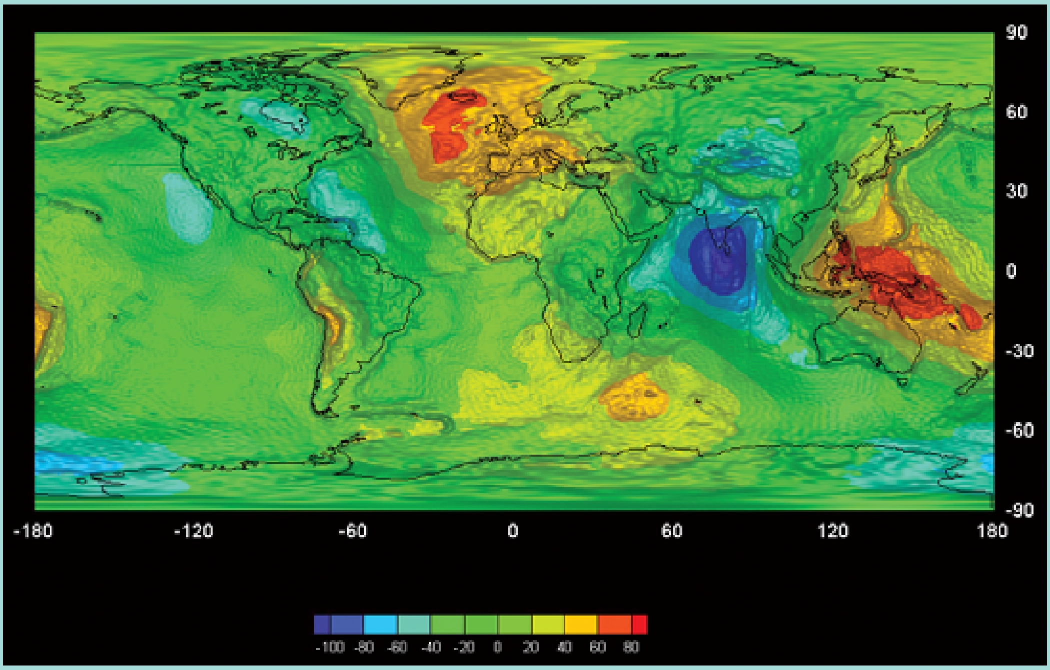


IMAGE: ESA – GOCE HIGH LEVEL PROCESSING FACILITY

GOCE first global gravity model

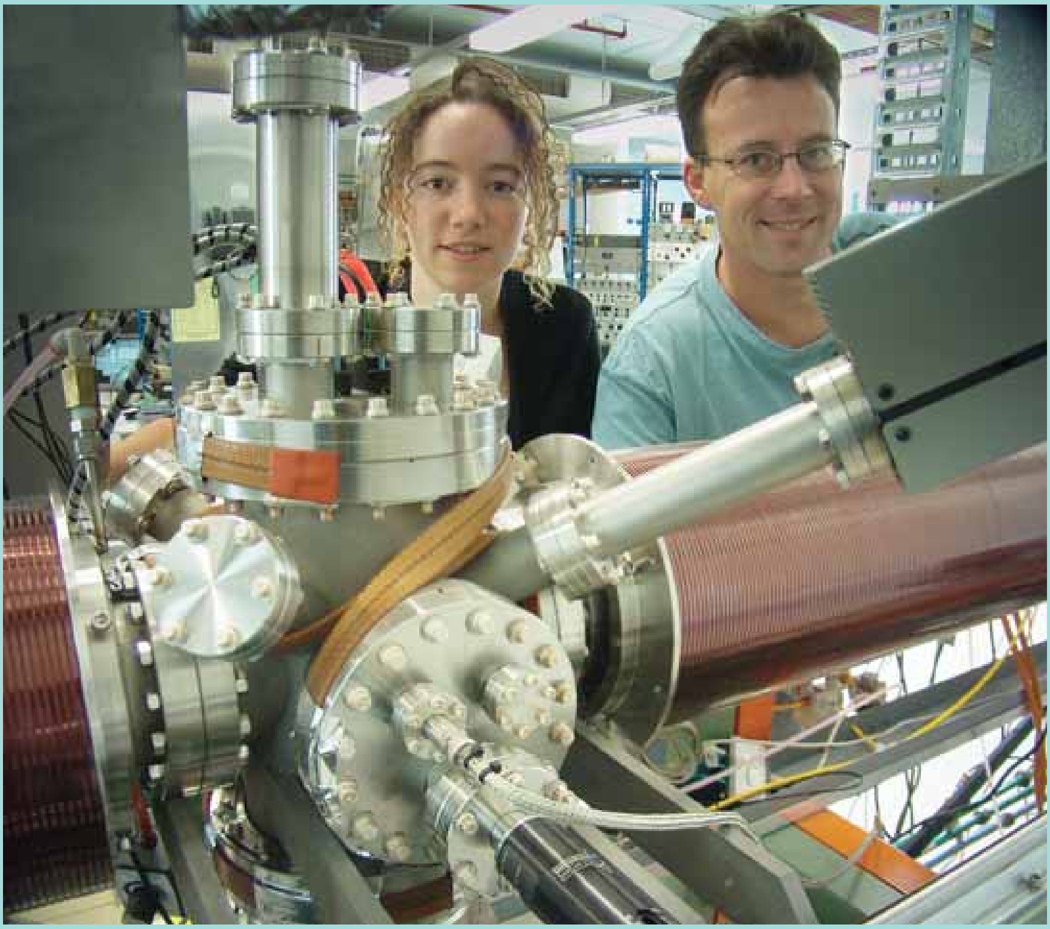
ANTIMATTER PROBES REVEAL FUNDAMENTAL PROPERTIES OF MATERIALS

The ARC Centre of Excellence for Antimatter-Matter Studies (CAMS) has a mission to lead Australia into a new and exciting area of research based on positron interactions in situations related to physical, chemical, material and biological sciences. The centre comprises seven nodes: the Australian National University, ANSTO, James Cook University, Flinders University, University of Western Australia, Curtin University and Charles Darwin University. CAMS has established itself as a world-class centre for antimatter research through the development of unique, world-class research infrastructure, drawing together Australian and international experts in collaborative partnerships. Successes so far are encapsulated, in part, in the 300+ refereed research publications, 150+ invited talks at international meetings, as well as more than 50 students engaged in the centre's research programs. An indication of the centre's international presence is that about half of the participating graduate students are from overseas, and that many graduates have been offered postdoctoral positions in leading international laboratories.

The centre's research covers a spectrum of activities from the fundamental to the very applied, using experimental and theoretical tools to study the interactions of positrons and electrons with atoms, molecules and materials in order to gain a better understanding of how antimatter interacts with matter. The research is focused in three broad themes: fundamental studies of antimatter-matter interactions; positrons and electrons as probes of materials; and applications of positrons and electrons to biology and medicine.

Looking further ahead, CAMS proposes to significantly increase its research capacity through strategies aimed at the development of next-generation positron sources, with positron fluxes in excess of 100 times what is presently available.

Website **www.positron.edu.au**



CRITICAL ISSUE 1: ACHIEVING A PHYSICS-LITERATE WORKFORCE AND COMMUNITY

Critical issue 2: realising human capital in physics

The Australian Government has reported that by 2020 the demand for researchers will outstrip supply (Research Workforce Strategy, 2011 [1]). There are three main reasons for the impending skills shortage:

- Australia has a disproportionately high number of researchers approaching retirement age
- Australia is not training enough researchers
- increasing global competition for research skills will result in an inadequate number of trained researchers migrating to Australia.

In the context of physics, the below-average growth rate in student numbers enrolled in the physical sciences and mathematical sciences is a cause for major concern, and relates to the second point above. It is also likely to mean that in the future there will be insufficient numbers of physics graduates flowing into the private and government sectors, particularly into positions where the requirement is for well-developed problem solving and analytical skills as opposed to discipline specific knowledge. These skills are critical because the 21st century promises extraordinary advances in our understanding of the fundamental questions in physics, and in the application of physics to revolutionising our society. It is of key importance that Australian physics research continues to pursue research themes and questions that are of high scientific and global importance. Unaddressed skills shortages in the physics research sector threaten the maintenance of Australia's technological capability, our participation in such discoveries, and our ability to work in international and interdisciplinary teams.

A large proportion of senior physicists are currently responsible for maintaining high-quality research outputs that seed the technology pipeline. Their international reputation has ensured that the Australian physics research sector is a valued research partner in international research programs.

Failure to ensure that the next generation of research leaders are able to continue to produce research outputs of equal excellence and impact will jeopardise the sustainability of the physics research system. Also, Australia has a strong record of trained physicists diffusing into cognate disciplines including medicine, finance, meteorology and beyond. Strategies to ensure students are attracted to a career in physics, and that trained physicists are retained and attracted to the profession are critical.

In particular, strategies to attract and retain highly skilled but vulnerable members of the physics community must be adopted. This includes women who are less likely to choose a career in physics and physicists (predominantly female) whose career progression does not follow a linear path due to the impact of family and/or competing responsibilities. The difficulties of re-entering the physics workforce after taking time out for family, to broaden skills (for example, to gain experience in industry or policy development) or due to other commitments results in challenges to career progression, retention and promotion. This is further exacerbated by the standard performance metrics upon which career progression largely depends; metrics which are typically heavily weighted by publications, successful grants and various forms of peer recognition. Early-career researchers are also vulnerable as they have limited job security due to their high dependence on short-term competitive grant funding.

Strategies must be found to address the special circumstances faced by Indigenous people accessing and completing advanced studies in physics and other disciplines. Data for the participation rate of Indigenous students in physics education is scarce; however, anecdotal evidence suggests these participation rates are extremely low.

Universities Australia has identified four key areas for attention: improving the academic preparedness of prospective Indigenous students; developing alternative pathways into higher education; academic and personal support for Indigenous students once enrolled; and improved financial support. The inspiration of David Unaipon shows

1 http://www.innovation.gov.au/Research/ResearchWorkforceIssues/Pages/default.aspx

Enhancing potential with a physics education?

David Unaipon left school at 13 without any formal education in physics but this remarkable inventor anticipated the helicopter in 1914. Unaipon was an extraordinary multi-talented Australian whose portrait now appears on the Australian fifty dollar note. As reported in the Adelaide newspaper *The Advertiser* Friday 31 July 1914, Unaipon was working on an invention 'to enable aeroplanes to rise vertically from the ground instead of running along for some time to gain impetus'. The report comments 'it occurred to him that the principles underlying the flight of the boomerang might be applied to aeroplane propellers, to do away with the preliminary run… it is a great mistake to suppose that its peculiar curve and flight are merely accidental'. As we now know, accounting for this 'peculiar curve' requires advanced physics including aerodynamics, the concept of angular momentum and the balance of forces acting on the boomerang. What might this exceptional Australian have accomplished if he had the benefits of a physics education?

that this issue needs to be addressed because, as the Universities Australia report concludes, 'higher education is a powerful vehicle for both personal and social advance. That advance should be more inclusive' [2].

Employment prospects and a variety of exciting career paths available to trained physicists should be well documented and communicated to ensure physics graduates have the best chance of contributing their skills to the diverse physics workforce.

Career and talent management are essential aspects of ensuring that talented physicists are identified and nurtured throughout their professional lifespan.

Large cohorts of physicists serve the nation in academia and government, in education and in industry. Government, in particular, is a major employer of physicists, mainly in research and advisory roles in its major research agencies such as the CSIRO, DSTO, ANSTO, and the Bureau of Meteorology. A major issue for government research and service agencies is the low number of available trained physicists graduating from university and entering a research career. Equally, industry is hungry for a healthy pipeline of physics-trained professionals.

Strategies to improve collaboration between industry and research organisations nationally and internationally must be devised and adopted. Improving this interface provides opportunities for speeding up the translation of discoveries into innovations. Issues such as intellectual property management by academic institutions and improved understanding of factors that affect the business environment (such as shareholder and customer demands) are central to improving partnerships between industry and research organisations. There are a number of successful models of industry collaboration with universities, for example in the mining, information and communication technology and biomedical industries (see table 5) that could be expanded or adopted in other industries.

A key factor to improving collaboration between industry and research is recognition of the weaknesses associated with the publication-based metrics applied in Australia which do not capture nor reward entrepreneurialism and interactions with industry. In the current system, not only is there no incentive for researchers to enter industry temporarily, there is a strong disincentive for doing so.

In this context, enormous opportunities exist for capturing the expertise of researchers in both the research sector and industry by the provision of better on- and off-ramps between research organisations and industry if these can be created without penalising career paths due to 'interruptions' that should in fact be recognised as opportunities to diversify skills and increase the impact of science.

The development of additional metrics that not only address research excellence but also reward cross-organisational transfer of skills and valuable expertise without penalising non-traditional research career paths is critical. For example, recognition and reward could be given to excellence in teaching, commercialisation, policy development, and cross-disciplinary, industry and technical expertise.

Strengthening interactions and scientific collaboration with cross-disciplinary teams, for example with engineering professionals, and the applied physics sub-disciplines will also provide diverse employment opportunities for graduates and allow industries to boost their research and development efforts and investment. For example, the mining and high tech scientific instrument industry sectors continually seek physicists and often source them from overseas, particularly from former Eastern Bloc countries as they cannot obtain sufficient numbers of highly qualified physicists from Australia.

2 http://www.universitiesaustralia.edu.au/resources/63/83

The opportunities for physicists pursuing careers outside the traditional discipline boundaries could be addressed at a Forum on Physics and Society similar to the program of the European Physical Society [3]. The forum would explore the challenge experienced by physicists leaving their usual fields of study, who pursue alternative careers outside teaching and university-based research. The forum could begin with a series of review presentations by physicists and other scientists who have experience in domains such as diplomacy, finance, health, industry and politics. Working groups at the forum could address key issues including the strengths and weaknesses of being a physicist, the global challenges where physicists have an important role, recommendations for the physics curriculum and the social responsibility of physicists. The European Physical Society forum recognised that knowledge alone does not create value: societies need 'real' production to sustain research and development. Less narrowly focused education systems, greater diversity and cross-discipline ties are needed, the forum said, along with more adaptation towards open systems.

There is also a need to have sufficient physicists to support large cross-disciplinary research programs that address research questions of high complexity. Of rising importance in the 21st century are complex problems such as securing our food, water, and power supply.

DECADAL OBJECTIVES

- Address skills shortages in the physics research sector by creating a healthy pipeline of physics-trained professionals
- Maintain Australia's excellent international reputation in physics and high-quality research output
- Train, attract, and retain physicists to and in Australia by maintaining and promoting the quality of Australian physics research groups and Australian research strengths
- Attract and retain vulnerable members of the physics community, including women, Indigenous Australians, early-career researchers and those taking career breaks to develop valuable skills
- Facilitate productive partnerships and mobility between academia and industry
- Enhance industry-driven applied and commercial research
- Promote greater participation of physics in interdisciplinary research

3 www.epsnews.eu/2012/04/forum-physics-and-society/

RECOMMENDED ACTIONS AND PATHWAYS

a) Equitable career pathways and removing disadvantage

- Provide equitable access to career by consistently enforcing research opportunity and performance evidence guidelines in assessing candidates for research positions and for internal and grant funding.
- Implement initiatives to recruit, retain and promote women and create an environment in which all staff can achieve their maximum potential.
- Reassess the standard performance metrics upon which career progression largely depends.
- Improve the academic preparedness of prospective Indigenous students, and improve personal and financial support once enrolled.
- Develop alternative pathways into higher education for Indigenous students.
- Reassess conditions for travel support. In the case of the ARC Future Fellowship Scheme (and its successors) the restrictions on non-fellow travel support are recommended to be lifted. At present restricting travel support only to the fellow discriminates against fellows who cannot travel because of carer responsibilities. Allowing fellows to use their ARC travel funds to support visits of key collaborators who will advance the cause of the project will remove this discrimination.

b) Partnerships between industry and academia

- Provide joint postdoctoral (as opposed to PhD) positions in industry, jointly funded by government, university and industry.
- Develop a 'Physics in Industry' model for constructive and lasting relationships between industry, business and the higher education sector based on the successful 'Mathematics in Industry Group' run by AMSI. This could be done by the AIP and the Academy of Science National Committee for Physics.
- Develop models for facilitating cross-sector mobility between higher education institutions, government research agencies and industry and business. This includes developing mechanisms and metrics that facilitate entrepreneurialism and commercialisation of research within research organisations without penalising career prospects.
- Convene, under the leadership of government, a summit or workshop with the aim of developing an understanding of mutual expectations of government, industry and academia, and to develop more effective modes of interaction and collaboration.

- Better manage intellectual property held by academic institutions.
- Improve understanding by physics researchers of factors affecting businesses (such as shareholder and customer demands).

c) The power of cross-disciplinary research

- Encourage the participation of physics in interdisciplinary consortia to address problems of national importance by encouraging research funding programs to aggregate critical mass without discipline restrictions.
- Develop schemes that support large coordinated multidisciplinary teams and ambitious research projects

Human capital in physics

Unlike the school education sector, the higher education sector staffing profile shows a breadth of both teaching and research expertise across all sub-disciplines with peaks in astronomy/astrophysics, condensed matter physics and optics and photonics. The student-to-staff ratio has increased in the university environment and is thought to be one factor which could harm student retention and further study [4].

Other research organisations such as CSIRO, DSTO and ANSTO are all involved with research in specific applications and deliver specialised advice, scientific services and products to government, universities, other research organisations, international organisations and businesses. These organisations each employ a large number of physicists; however, it is difficult to get an accurate measure of the exact number of physicists and their contribution to the research outputs of these organisations.

Physics education, research, industry, business and government service agencies depend on the availability of talented individuals. It is therefore important that such individuals are recruited and allowed to contribute their best efforts in the environment they choose for professional pursuit.

The visibility and promotion of the available physics career paths for school students and undergraduates needs to be high so students can evaluate up-front, the benefits, limitations and constraints of physics career paths in any of the physics community sectors. This visibility is currently low.

With the imminent dangers facing the education sector, the retention of talent already within the physics community becomes even more essential. The most vulnerable members of the physics community are women, who are already under-represented, particularly at senior levels (figure 7), and young researchers who rely on competitive grant funding. Women often follow a non-linear career path which is heavily influenced by family responsibilities and the career demands of their partner. The difficulties of re-entering the physics workforce after taking time out for family or other commitments result in challenges to career progression and barriers to promotion for many women. This is further exacerbated by the standard performance metrics upon which career progression often depends.

There are employment opportunities available for physics graduates with sound theoretical knowledge and practical skills, but job security is a problem for many physicists working in academic research. Also, the quality of the interaction between potential employers and academia can limit the identification of job opportunities for new graduates.

One-third of physics staff members within universities are research fellows employed on research grants, demonstrating the importance of funding agencies support to Australian physics research. The university staff profile is heavily weighted toward the senior end of the spectrum and the gender balance shows that women account for only 21 per cent of the staff (figure 8). This gender balance is mirrored by the new enrolments to PhD programs where the number of women has decreased over the last decade from just under 28 per cent to just over 21 per cent.

An emerging trend, most often seen at large US conferences, is the provision of childcare for delegates. This has been made part of the core responsibilities of the conference organisers. At the 2012 Materials Research Society Spring Meeting, grants of up to $300 were available to delegates who bring young children or who incur extra expenses for leaving them at home . Preference is given to early career researchers. Such practices and costs must become part of the standard responsibilities and financial package of organising large conferences.

OPPORTUNITIES

Opportunities exist for enabling equitable access to career paths. The endorsement and consistent application of the ARC's research opportunity and performance evidence principles in workplaces

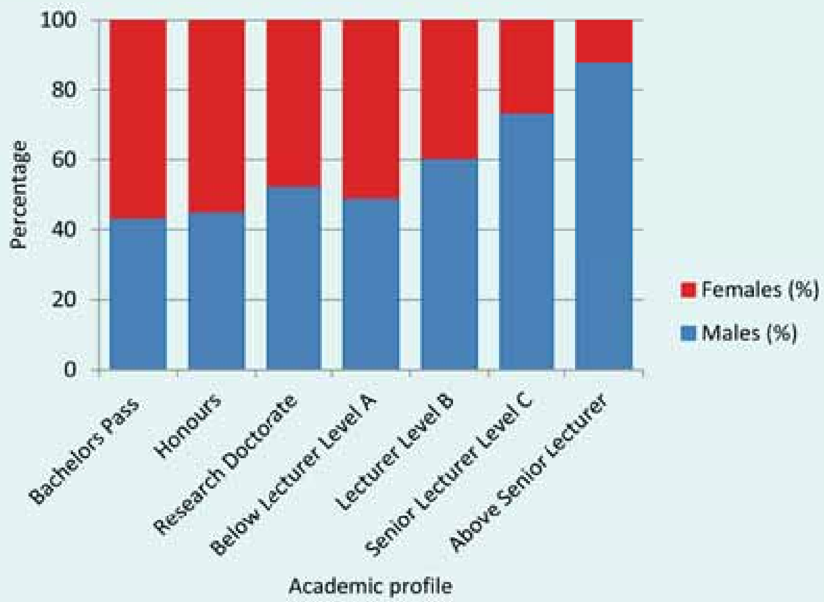
4 *Transforming Australia's higher education system*, Commonwealth of Australia (2009)

where promotion is based on research performance is an opportunity to make the intent of enforcing equitable access to research positions transparent.

Active campaigns to address these issues require recognition. A successful program has been implemented in the United Kingdom (UK). The Athena SWAN charter for women in science was established to recognise institutions committed to the advancement and promotion of women in higher education and research. Membership of the charter is granted to institutions that incorporate the following six principles into their action plans:

- to address gender inequalities requires commitment and action from everyone, at all levels of the organisation
- to tackle the unequal representation of women in science requires changing cultures and attitudes across the organisation
- the absence of diversity at management and policy-making levels has broad implications which the organisation will examine

Figure 7: Academic profiles by gender; natural and physical sciences 2007

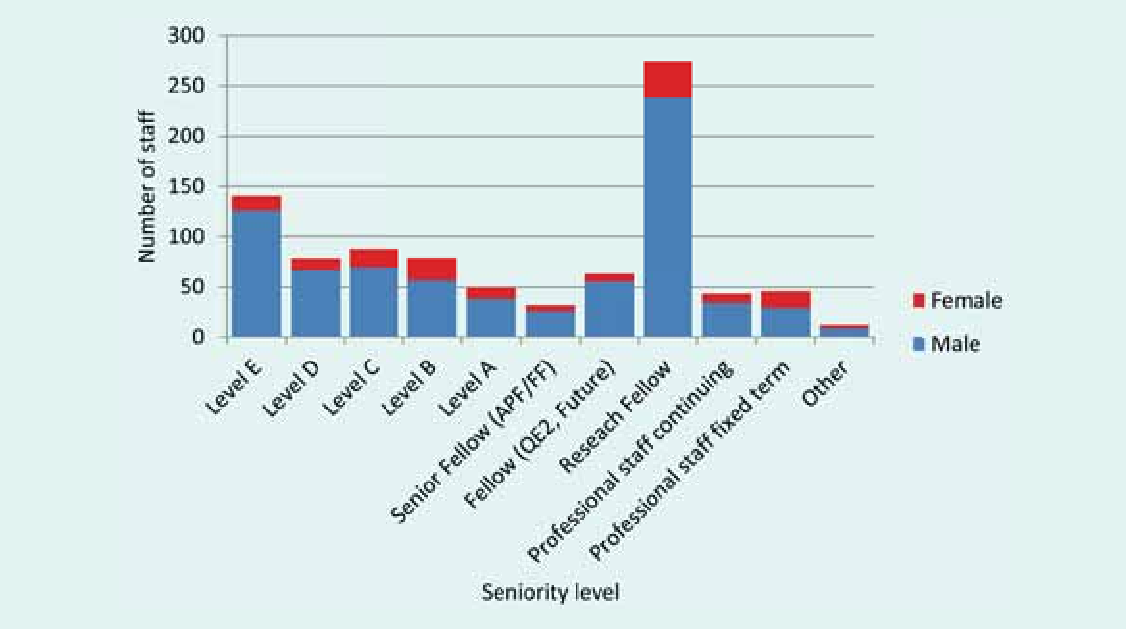


Source: *DEEWR Selected higher education student statistics 2007, DEST special report FTE staff in AOU groups 2007*.

Table 4: Research staffing profile of physics sub-disciplines as reported in ERA 2010

	Head count						
Discipline	**Level E**	**Level D**	**Level C**	**Level B**	**Level A**	**Other**	**Total**
Physical sciences (02)	**143**	**109**	**174**	**309**	**216**	**387**	**1337**
Astronomy and space sciences	40	23	26	72	34	103	299
Atomic, molecular, nuclear, particle and plasma physics	23	17	35	34	31	57	197
Classical physics	4	6	7	12	7	25	61
Condensed matter physics	29	21	36	57	52	62	257
Optical physics	24	23	31	64	46	48	237
Quantum physics	9	7	11	22	11	11	72
Other physical sciences	13	11	28	48	35	80	214
Mathematical physics (0105)	10	8	13	18	14	11	75
Geophysics (0404)	16	10	19	20	16	37	117
All 'Physics' sub-disciplines	**169**	**127**	**206**	**347**	**245**	**435**	**1529**

Figure 8: Distribution of staff in Australian university physics by seniority



- the high loss rate of women in science is an urgent concern which the organisation will address
- the system of short-term contracts has particularly bad effects on the retention and progression of women in science, which the organisation recognises
- there are both personal and structural obstacles to women making the transition from a PhD into a sustainable academic career in science, which require the active consideration of the organisation.

About 70 universities in the UK have achieved membership. Aspiring to membership of the charter can motivate initiatives to recruit, retain and promote women and create an environment in which all staff can achieve their maximum potential. Publicity upon achieving membership can enhance an institution's status, highlight initiatives that would otherwise not be visible from outside the institution and act as an incentive for qualified applicants for positions. A similar program in Australia for institutions that employ and train physicists may, in any case, be required to compete for human capital from around the world.

Opportunities also exist for developing additional metrics that not only address research excellence but also, for example, excellence in teaching, commercialisation, or cross-disciplinary, industry and technical expertise to facilitate the cross-organisational transfer of skills and valuable expertise without penalising non-traditional research career paths.

Physics into industry

There are a number of successful models of industry collaboration with universities with prominent examples in the mining, information and communication technology and biomedical industries (table 5). Industry and business has employment opportunities for Australian physicists and would benefit from a higher number of physics graduates.

Government is also a major employer of physicists, mainly in research and advisory roles in its major research and service agencies such as the CSIRO, DSTO, ANSTO, the Bureau of Meteorology and others. A major issue for government research and service agencies is the low number of available trained physicists graduating from universities and entering a research career.

To achieve more productivity in industry will require closer collaboration between industry and research organisations nationally and internationally. Opportunities can be seen in strengthening interactions and scientific collaboration with cross-disciplinary teams, for example with engineering professionals, and the more applied physics sub-disciplines.

Strengthened relationships with industry will also highlight employment opportunities for graduates and allow industry to identify talent and access capable graduates for employment.

The industry and business sector in Australia is very active in research and development, contributing (by funding) 68 per cent of the increase in total gross

SIR ALAN WALSH AND ATOMIC ABSORPTION SPECTROSCOPY — AN AUSTRALIAN INVENTION

The Australian Institute of Physics awards the Walsh medal every second year. This award, an initiative of the New South Wales Branch of the AIP, recognises significant contributions by a practicing physicist to industry in Australia. It commemorates the late Sir Alan Walsh FAA FTS FRS, one of Australia's most eminent and distinguished scientists, the originator and developer of atomic absorption spectrophotometry, who pioneered its application as a tool in chemical analysis.

Alan Walsh was born in 1916 in the UK and concluded his undergraduate and postgraduate studies in the physics department at the Manchester College of Technology in the UK. The atomic absorption method of chemical analysis has been described as 'the most significant advance in chemical analysis' in the 20th century. Alan Walsh was the leader of the spectroscopy section of the CSIRO Division of Chemical Physics in Melbourne (1946–57) and assistant chief of the division (1958–76). This division had the aim to apply modern physical techniques to the solution of chemical problems. His interest in atomic absorption spectroscopy was a result of two interacting experiences: one of the spectrochemical analysis of metals over the period 1939 to 1946; the other of molecular spectroscopy up to 1952.

The first public demonstration of a working atomic absorption instrument was in March 1954 at an exhibition of scientific instruments held by the Victorian Division of the (then British) Institute of Physics at the University of Melbourne. Atomic absorption provided a quick, easy, accurate and highly sensitive method of determining the concentrations of more than 65 of the elements, rendering traditional wet-chemical methods obsolete. The method has since found important application worldwide in areas as diverse as medicine, agriculture, mineral exploration, metallurgy, food analysis, biochemistry, the wine industry and environmental control.

Bringing the method from the laboratory into commercial production was not an easy path. An attempt to commercialise the technology via a license agreement through Hilger and Watts in the UK failed and it took several years until in 1962 Techtron Pty Ltd, a small Australian company based in Mulgrave, was again interested in commercialising the instrumentation.

The first spectrometer based on his design was produced by Techtron in 1964. In August 1965, Techtron Appliances Pty Ltd merged with Atomic Spectral Lamps Pty Ltd to form Techtron Pty Ltd, which manufactured the Model AA-4 with a synchronously tuned amplifier and a nitrous oxide-acetylene burner. This was followed by a period of rapid growth, with staff increasing to around 200 in 1966.

Techtron Pty Ltd was approached by Varian Associates, a successful instrument manufacturing company in Palo Alto, California, with an offer of acquisition, first a 50.5 per cent holding and progressing to 100 per cent over five years. This was followed by further rapid growth, with sales increasing at an average of 30 per cent a year for the next six years and staff growing to 630 by 1972. The company continued to become Varian Australia Pty Ltd, the second-largest manufacturer of atomic absorption equipment in the world, exporting more than two-thirds of its output. Varian has now been acquired by Agilent Technologies.

expenditure on research and development from 1984–85 to 2006–07. However, Australia performs poorly in terms of introducing new products to market, ranking at the bottom of the OECD tables on technological innovations that are new to the world.

The operating environment for industry is generally determined by government legislation such as research and development taxation rebates and regulations directed at building industry competence and competitiveness.

The academic sector is often perceived as being inwardly focused and driven by publication outputs and impact goals to secure future funding, rather than working to forge strong alliances with industry. On the other hand, industry can perceive academia and research organisations to have limited interest in solving the problems that face business and industry, and a lack of understanding of the constraints under which industry operates. The demands of shareholders, the demands of customers, the risk of obsolescence and the need to make a profit are seemingly not well understood by the academic research sector.

The publication-based metrics typically do not capture entrepreneurialism and interactions with industry, despite government attempting to facilitate the interchange of scientists between the research sector, industry and business.

The underlying issue is that, not only is there is little incentive for researchers to partner with industry temporarily, but the current metrics introduce disincentives, particularly as the research opportunity and performance evidence guidelines may be applied inconsistently.

Finally, the below-average growth rate in student numbers enrolled in the physical sciences, mathematical sciences and chemical sciences mean that in future there will be insufficient numbers of physicists to ensure effective collaboration with the

Table 5: Different models of industry collaboration with research providers

Model	Advantage for company	Disadvantage for company	Comments
Short-term contract research at full cost	All IP owned by company. Mostly used for smaller projects at the applied end of the research scale. Tendency to contract to close-by research providers.	Project management skill of research providers is low. Time lags to project start often exceed company expectations.	Manufacturing companies may seek support in solving specific applied problems which might be of low-to-moderate interest to the research provider. Initiatives such as the opportunity provided by government to place a scientist with industry for a few months is not aligned with current research-career metrics.
CRC model	Access to a number of research providers.	IP policies of CRCs are only conducive to research on industry problems that do not directly affect the competitiveness of individual companies. Lag time to application of research is long.	Advanced manufacturing CRC
Medium-term research project at shared costs (e.g. three years) with research department and individual research leaders	Access to specific research providers in the field of expertise required without having to invest in long-term employment and infrastructure, use of research provider skills and infrastructure.	Poor project management skills of research providers. IP policies of research providers may be too disadvantageous to deal with.	Management of expectations of both parties is often an issue. The model is often used by companies who want to have exclusive rights to the beneficial use of the created IP. Increasingly companies take on the role of project management to reduce the risk of delays and cost overruns.
Long-term collaborative programs with research providers in their country of operation	Long term partnership at department and/or organisational level, usually for a number of years. Access to research infrastructure and skills. Can pick and choose research providers globally.	Management of expectations and management of projects and long-term programs. The best research groups might not be in countries where the company has their headquarters or their research and development department. Taxation regulations may not make setting up of long-term relationships easy or profitable.	Several different models, such as contracts amounting to several millions to multimillions, setting up of industry research centres on campuses with related infrastructure, or co-location of separately funded and operated industry and research provider groups. Tendency to establish long-term relationships where the end markets for products are and where there is already an established research and development footprint of the company in the country.
Open innovation	Create and exploit new sources of ideas and IP.	Often ill-defined goals and expectations, resulting in confusion.	Difficult to manage, track and capture mutual benefits. IP issues need to be dealt with up front.

DEVELOPMENT OF THE GLOBAL QUANTUM INFORMATION NETWORK

The Centre of Excellence for Quantum Computation and Communication Technology is one of the largest, internationally coordinated research efforts in quantum information technology that capitalises on Australia's strength in quantum physics to develop the science and technology of a global quantum information network. In particular it encompasses ultra-fast quantum computation and absolutely secure quantum communication towards the long-term goal of distributed quantum information processing. Funded by the Australian Research Council, the US Army Research Office, Australian universities, the New South Wales State Government, the Department of Defence, and industry partners, the centre hosts approximately 150 researchers in an international research effort.

The centre comprises three main interlinking research programs in optical quantum computation, silicon quantum computation and quantum communications across six Australian universities, together with 12 formal international partners. These partners come from academia, government and industry and include both national and international companies such as Toshiba, IBM, ZyvexLabs and QuintessenceLabs. The research programs focus on the development of cutting-edge technology to observe, manipulate and control the quantum properties of individual atoms and photons of light, thereby understanding and harnessing their information processing power.

Over the past decade the centre has established a leading position internationally, with a number of significant results, including the first single-atom transistor, quantum logic gates using single photons of light, read-out and control of information encoded on a single electron in silicon, the longest quantum memory of stored light, and the first application of a quantum probe in a living cell. The long-term outcomes promise to transform Australia's technological sophistication and future capacity for innovation, establishing access to unprecedented communications security and computing capability for Australia.

See **www.cqc2t.org/**

IMAGE: COURTESY OF CENTRE FOR QUANTUM COMPUTATION & COMMUNICATION TECHNOLOGY WWW.CQC2T.ORG

growth disciplines and technology development in the private and government sectors.

Physics and interdisciplinary research

A report from the Massachusetts Institute of Technology, *The third revolution: the convergence of the life sciences, physical sciences and engineering* [5], discusses some of the complexities of interdisciplinary research and proposes a new paradigm that can yield critical advances on problems in the health sciences. The authors foresee advances in information technology, materials, imaging, nanotechnology, optics and quantum physics coupled with computer modelling that will transform the life sciences. When suitably engineered, new systems will provide advances in biofuels, biomaterials, viral self-assembly and health research. This will trigger a 'third revolution' in the life sciences that follows the first revolution in molecular and cell biology and the second revolution in the rise of genomics.

This is but one example of an international trend toward tackling global issues facing humankind via interdisciplinary approaches. The future of physics

5 web.mit.edu/dc/Policy/MIT%20White%20Paper%20on%20Convergence.pdf

research will lie not only in international collaboration but also in the expansion of interdisciplinary research. It is vital for the health of physics research in Australia that these international trends are recognised and that our approaches to funding and assessment of research adapt to incorporate the opportunities available in this changing environment.

SEARCHING FOR GRAVITATIONAL WAVES

After 40 years of effort the first direct detection of gravitational waves appears to be imminent. Gravitational wave detectors of greater and greater sensitivity have been developed. The earlier generations of detectors were only sensitive enough to detect rare nearby or unexpected sources. The latest generation of detectors is designed to have sufficient sensitivity to detect known sources — coalescing neutron stars — at a rate of several times per year. Even more signals are expected from coalescing pairs of black holes.

Australia has played a strong role in the development of gravitational wave detectors over the past two decades. In the 1990s the Australian detector 'Niobe' was a member of an array of four worldwide detectors called the International Gravitational Events Collaboration that set significant limits on the rate of gravitational wave bursts from the Milky Way.

Researchers from five 'Group of Eight' universities formed the Australian Consortium for Gravitational Astronomy in the 1990s. In 2000 they began development of a research centre at the Gingin site in Western Australia designed to host a future southern hemisphere gravitational wave observatory. About $30 million has been invested in the development of this facility and an associated public education centre.

This Australian consortium has a strong program of research in the advanced technologies that underpin the new generation of detectors: high power laser optics, vibration isolation, quantum measurement, advanced data analysis and study of sources. The consortium is closely involved in international projects, especially the US-led Advanced LIGO project, which is building two detectors in the USA and plans one in India.

An array of at least six detectors across the planet is necessary for both noise reduction and signal detection. The international community has set a high priority on the construction of a southern hemisphere detector, because it confers the greatest possible advantage on the array sensitivity and angular resolution. Such a detector would allow Australia to exploit its ideal geographical location and to become the regional focus for exciting frontier technologies. An Australian observatory would incorporate locally and internationally developed technologies in precision laser optics, quantum measurement, vibration isolation and innovative vacuum pipe manufacturing. It offers numerous spin-off technologies and substantial training benefits. Over the years Australia has been offered several partnership opportunities for the development of an Advanced Gravitational Wave Observatory.

www.anu.edu.au/Physics/ACIGA/

PHYSICS AND CLIMATE CHANGE

Everybody talks about climate change — and physical sciences are at the core of this topic. The debate about the likely effects of rising greenhouse gas emissions combined with economic growth on the global climate and our living conditions, and the response we all should show to avoid potential disasters, is one of the big divisive and yet important topics for the next decade. Without the constant advances in physics, through new instrumentation, analytical insights into the behaviour of complex systems such as the atmosphere and the oceans, and the ability to make more and more reliable large-scale models, we would not have the data to know about the present state of our planet nor make any predictions about likely future developments.

Australian researchers are using state-of-the-art instrumentation based on physics-based technologies in important parts of the climate and key ecosystems, including the Southern Ocean, the Great Barrier Reef and Antarctica [1]. CSIRO teams refining climate forecasts include many physicists and mathematicians. The modelling required to fine-tune economic tools such as emission trading and taxation involves many physics-trained information experts.

The solution for a low-emission future will require development of alternative sources of power including solar, nuclear, wind, wave energy, geothermal and nuclear fusion. All of these involve research done by physicists to find better materials such as superconducting cables, quantum dot enhanced solar cells and grapheme-based electronics to name a few.

The creation of better power-conversion systems and safety devices and the efficient and smart distribution of power in our national networks are major challenges for engineers using the latest devices developed by physicists.

Unlike our competitors in Europe and Asia, Australia still has among the highest power and water consumption per capita in the world [2]. Energy-efficient transportation, communication, food and clean water production are all key challenges requiring new physics research now to produce solutions that will be available in one or two decades.

These topics are now some of the stated research priorities in Australia. They are a dominant part of the funding in engineering and physics provided by the Australian Research Council [3] and in special research initiatives supported by the government and industry through, for example, the Clean Energy Finance Fund [4]. Australian scientists provide key answers and set records in technological achievements. To serve these important goals new generations of physics-trained scientists are urgently required.

[1] The Science of Climate Change ASS 2010, www.science.org.au/policy/climatechange.html

[2] UN world energy report

[3] ARC annual report 2011

[4] http://www.ret.gov.au/energy/clean/Pages/CleanEnergy.aspx

Critical issue 3: building on physics research and investment

The physics track record

Australian physicists have a proven track record in high-quality research and technological outputs. Nonetheless research productivity could be improved by reducing the cost associated with preparing applications for competitive grant schemes. In 2011, 22 per cent of Discovery Program Grant applications were successful. Preparation of all 4100 applications in that year was conservatively estimated to cost $54 million in labour from the applicants. Implementation of a two-stage 'white paper' system would simplify the process. In the first stage investigators would support a brief white paper on the important innovation in their proposal. This would be less costly to prepare and could be rapidly assessed by the ARC College. First ranked white papers would be eligible to progress to the second stage which would be a full proposal similar to the present system. By reducing the administrative burden, resources are freed up to make the system more efficient, more agile and less costly to run. Two rounds per year may be possible to reduce the up to two year lag between development of a good idea and the opportunity to receive financial support.

Maintaining and expanding research infrastructure, including super-computing infrastructure, is essential to attract the world's best and brightest physicists and national and international collaborators. Physicists based overseas come to Australia to work and participate in our national programs, to conduct joint research in our national centres and institutes, and to gain access to major Australian infrastructure including the Synchrotron, the OPAL reactor and NCRIS facilities such as the Australian National Fabrication Facility.

Importantly, operational costs associated with large research infrastructure must be considered in the infrastructure investment strategy. Staff, operational and maintenance costs must be factored into infrastructure investment for Australian physics research to remain at the cutting edge and to maintain international collaborations.

It is therefore essential to have in place schemes that support the development of new physics research infrastructure, such as the capability areas supported by the National Research Infrastructure Council and NCRIS that identifies national capabilities and appropriately funds them.

With few exceptions, the theoretical physics/mathematical physics community in Australia consists of dispersed individuals or small groups with high international profiles and extensive international collaborations. There is a clear opportunity to develop mechanisms in Australia to create a network that capitalises on the demonstrated benefits that come when the community coordinates its activities at a national level, including achieving critical mass for the provision of advanced graduate-level coursework. While undergraduate education in physics in Australia tends to be generalist and caters to a broad spectrum of abilities and interests, advanced coursework is very important for students undertaking graduate studies in theoretical/mathematical physics. Small postgraduate numbers at any one institution makes teaching advanced graduate courses uneconomical.

Similar successful examples of this include the Australian Mathematical Sciences Institute (Australia), the Perimeter Institute (Canada), the Kavli Royal Society International Centre (UK), the Newton Institute (UK) and the Korean Institute of Advanced Study (South Korea). Institutes such as these have had a major impact on the field by supporting conferences, seminars and workshops, travel and networking opportunities for leading researchers, and also acting as a focal point for coordination with international agencies.

An Australian Theoretical Physics Institute would be an essential piece of infrastructure to support theoretical activities in physics, however, under current infrastructure funding guidelines no source of funding for essential infrastructure of this type exists.

Overemphasis on too few measures of performance and success can have limitations and conflict with an organisation's desire to recognise performance and good practice. It is important that metrics are developed for activities other than publication output. For example, it is important to recognise and reward efforts made to partner with industry or other disciplines, commercialise or assist government with policy formulation. Equally, organisations should be required to report on their activities to ensure equitable practices that can lead to removal of disadvantage for vulnerable sections of the workforce.

Human capital systems that should be measured encompass leadership systems, governance, career planning and pathways, talent retention and creation, and remuneration. Performance measurement for these areas really should be in place for an organisation to be sustainable.

In addition, field of research classifications and related metrics should be used accurately to reflect the current physics sub-disciplines and more importantly, their different publication and citation modalities.

As the 21st century unfolds, it is clear many Australian physicists are developing research interests and expertise in interdisciplinary fields that have a theme related to climate change and sustainability. Often research projects in this field are towards the 'applications' end of the innovation continuum as expected for projects that address challenging near-term problems of crucial importance to our society. In general, it was clear from interviews with stakeholders that there was a frequent perception that interdisciplinary research towards the 'applications' end of the continuum did not fit well with the 'discovery' focus of the ARC system. The proposals that are highly ranked in the ARC assessment system, but are not selected for funding, have the potential to be supported by other schemes that specifically support innovative proposals with a climate change and sustainability focus either as a near-term or long-term justification. These highly ranked proposals submitted to the ARC system, with therefore exceptionally high promise of high-quality research in all respects and flow-on benefits to the nation, could be submitted to, for example, the Clean Energy Finance Corporation [1] to find ways to support these 'shovel ready' projects already assessed as worthwhile by the rigorous ARC processes. If the projects are supported by this mechanism, the outcomes could be rigorously assessed and progress monitored by the standard processes and hence this is a safe and worthwhile investment in our nation's future. The quality outcomes from this class of proposals will improve the perception of government sustainability initiatives.

DECADAL OBJECTIVES

- Improve efficiency of funding agency processes to maximise impact of public investment
- Increase the global competitiveness and impact of the Australian physics sector by long-term investment in research infrastructure and human resource capabilities
- Diversify physics research financing sources
- Find ways to support 'shovel ready' ARC proposals with a sustainability theme assessed as worthwhile by the rigorous ARC processes through liaison between the ARC secretariat and the managers of the Clean Energy Finance Corporation
- Ensure overhead, personnel and operational costs of infrastructure are included in infrastructure funding schemes that support the development of the next generation of physics research facilities.

RECOMMENDED ACTIONS AND PATHWAYS

a) Efficient, agile, fair and sustainable research funding

- Minimise the administrative burden and make efficient funding agency processes by streamlining the ARC grant application process and moving to a two-stage 'white paper' system.
- Simplify funding schemes that support physics research, including a simplified process for grant renewal beyond the initial three years for projects of demonstrated significant achievement.
- Collaborate with the major funding agencies to improve agility of the funding process to enable responsiveness to international research opportunities, some of which arise at short notice, by the introduction of a new international collaborative research scheme.
- Ensure that there are funding schemes to support large collaborative centres of excellence in physics funded adequately at the top end of discipline funding. Physics research in areas of global and technological importance specifically requires large interdisciplinary teams to make an international impact.

1 www.ret.gov.au/energy/clean/Pages/CleanEnergy.aspx

Table 6: Number of ARC-funded physics research projects and funding allocation for the ten-year period from 2002 to 2011

Discipline	Number of ARC projects for commencement from 2002 to 2011	Funding for ARC projects for commencement from 2002 to 2011 ($ million)
Astronomical sciences, astronomical and space sciences	239	132.96
Theoretical and condensed matter physics, condensed matter physics, mathematical physics, quantum physics	261	169.43
Optical physics	206	111.53
Atomic, molecular, nuclear, particle and plasma physics	153	104.78
Other physical sciences	116	54.83
Geophysics	61	13.51
Classical physics	31	11.82
Total	**1067**	**598.86**

b) Infrastructure investment to remain at the cutting edge

- Providing ongoing funding for the NCRIS process to support major national physics infrastructure upgrades and operational costs, including the provision of qualified support staff.
- Broaden the ARC definition of 'infrastructure' to accommodate the non-physical infrastructure, critical for the theoretical and mathematical physics community in the development of an institute.
- Establish a 'Landmark Funding Scheme' to support major research initiatives (the order of $100 million or greater) that fall outside the scope of current funding schemes. Missed opportunities due to the lack of such a scheme include the recently proposed location of the third Laser Interferometer Gravitational-Wave Observatory (LIGO) detector in Australia.
- Develop a system to allow small to medium enterprise to access supercomputers to bypass cumbersome prototyping phase in product development.

c) Metrics and coding for the 21st century

- Develop metrics for academic activities that are broader than those based simply on publication output and citations, including measures of interaction with industry, commercialisation and the commercial impact of applied research.
- Develop an expanded set of metrics for university staff that can be used for tracking progress and process improvements (such as equity-related activities, achieving diversity of funding, meeting milestones in attracting new talent, developing collaborative programs etc.).
- Ensure that the research metrics and classifications used accurately reflect the current physics sub-disciplines and more importantly, their different publication and citation modalities.
- Ensure that the Australian Bureau of Statistics and DIISRTE re-examine field of research (FOR) codes for their appropriateness in the current scientific environment.

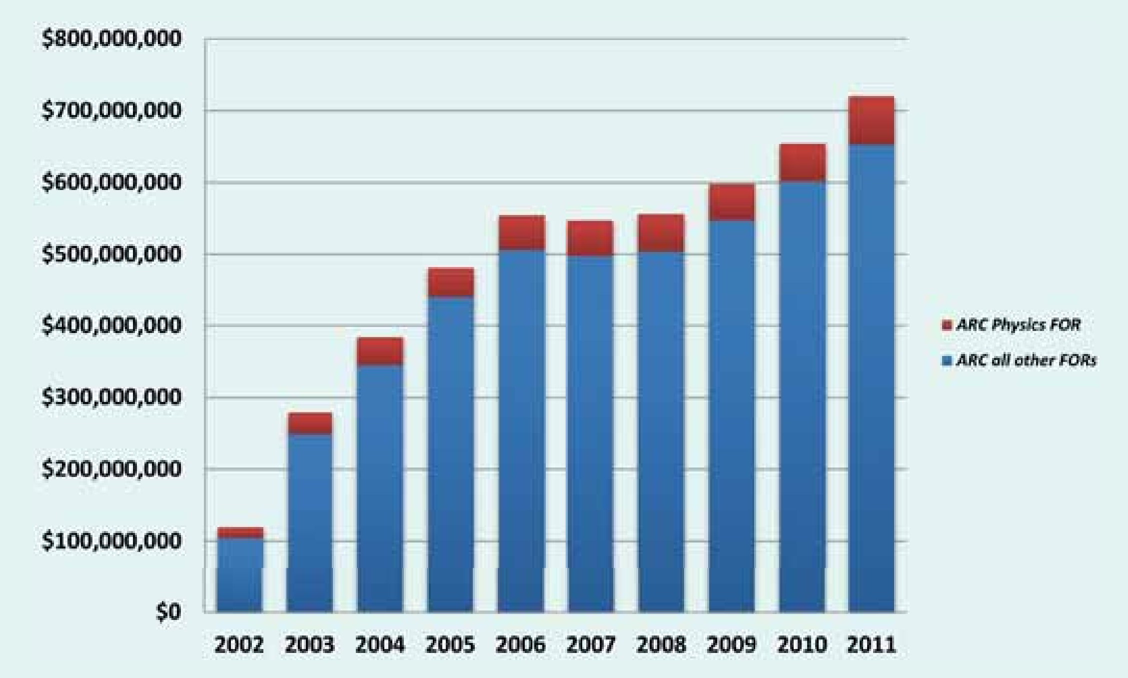
Physics research investment

Australian physics research has been very successful in attracting competitive funding. However, opportunities exist for expanding the breadth of funding schemes to cater for the specific needs of the physics research community. Specifically, there is a continued need to support large infrastructure including related technical support for maintenance and upgrading. There is also a need for investing in the creation of a Theoretical Physics Institute.

Reflecting the high standard of physics in Australia is the proportion of funding allocated to physics research projects by the ARC. The allocation of ARC funds to physics research continues to increase as a proportion of total funding allocations (table 6; figures 9–11). The ARC Centre of Excellence scheme is well suited to the physics research community where the ability to solve significant and important problems in physics requires the coordination of large teams with complementary skills in experimental and theoretical physics. Physics research funding has significantly benefited from this scheme.

Australian universities have been very successful in receiving competitive grant income from several

Figure 9: ARC annual allocations for physics FOR and all other FORs, 2002–11



Figures 9–11 compiled by H Bachor based on data provided by the ARC. Here physics grants are defined by allocations to applications made under the FOR code for physics. There are other projects, fellowships and centres which are based on physics research classified under other FOR codes.

sources and especially the ARC. However, physics research can be expanded more substantially through more novel schemes that address the specific needs of Australian physics.

Maintaining and expanding research infrastructure, including super-computing infrastructure, at a level that is effective in supporting the continuous drive for excellence of Australian research organisations is essential in the quest to attract the world's best and brightest young physicists and national and international collaborators. The Australian Government's Sustainable Research Excellence initiative has an essential role in this endeavour. As reported by Frank Larkins [2] in his analysis of the initiative, the indirect research cost funding has increased from 18 cents per Australian competitive grant dollar in 2008 to 30 cents in 2012. For physics, this initiative is very welcome because physics research typically depends on large and complex physical infrastructure that is costly to develop and maintain. Therefore the Sustainable Research Excellence initiative will have a proportional positive effect on the infrastructure supporting the physics research system. While the funding has tended to follow the concentration of research funds, Larkins points out that this is essential for Australia to maintain its international competitiveness.

2 www.lhmartininstitute.edu.au/userfiles/files/Blog/Sustainable%20Research%20Excellence_230712.pdf

The community looks forward to further increases to 50 cents in the dollar to 2014. There is a diversity of views in the physics community about the wisdom of the concentration of resources for physics research infrastructure.

Larkins concludes: '*The present policy of a competitive "market driven" approach is leading to increased concentration of the national research effort into fewer universities consistent with government policy. The competitive bidding costs to individual universities to achieve this outcome are very high. The present approach may not be the most optimal way to obtain the desired returns on the national research investment. A broad policy discussion of the costs and benefits of current practices and possible alternatives is warranted.*' Consistent with views expressed during the decadal plan process, this policy discussion would also be supported by the physics community.

There are some limitations to the ARC system, the most important system for funding physics research in the tertiary sector. Firstly, cross-disciplinary research is not well supported by the current funding system. Secondly, the current funding system does not fully cover the cost of research projects, which significantly limits the amount of research that is possible for some organisations. Thirdly, academics are experiencing an increasing burden of administrative and

Figure 10: Funding in physics defined by FOR code, 2002–11

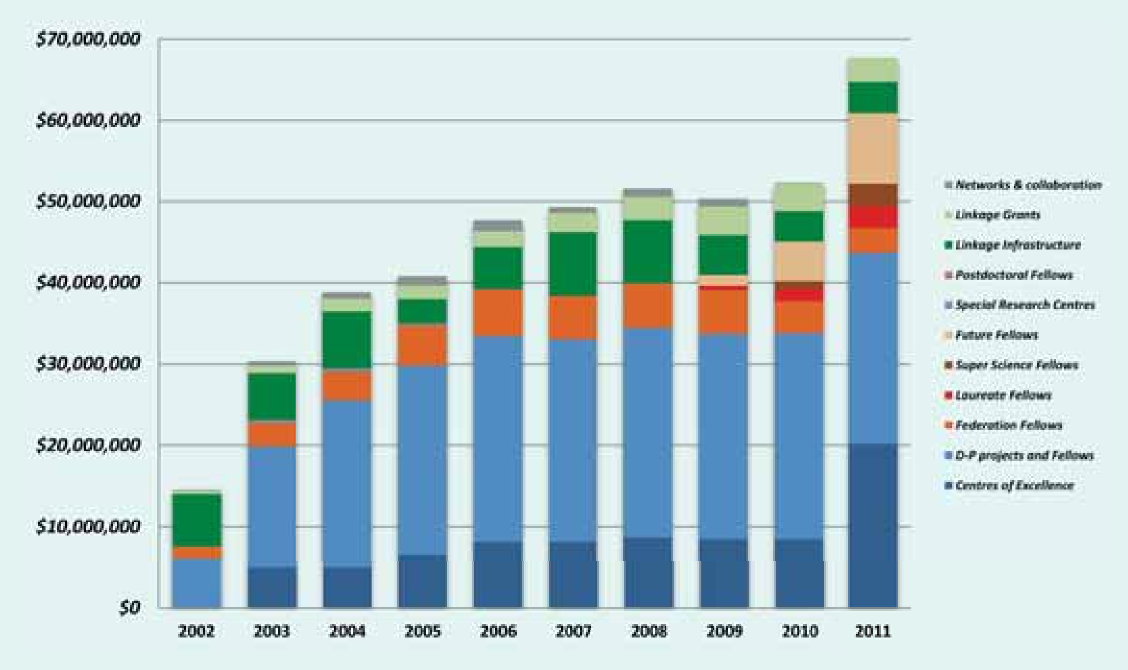
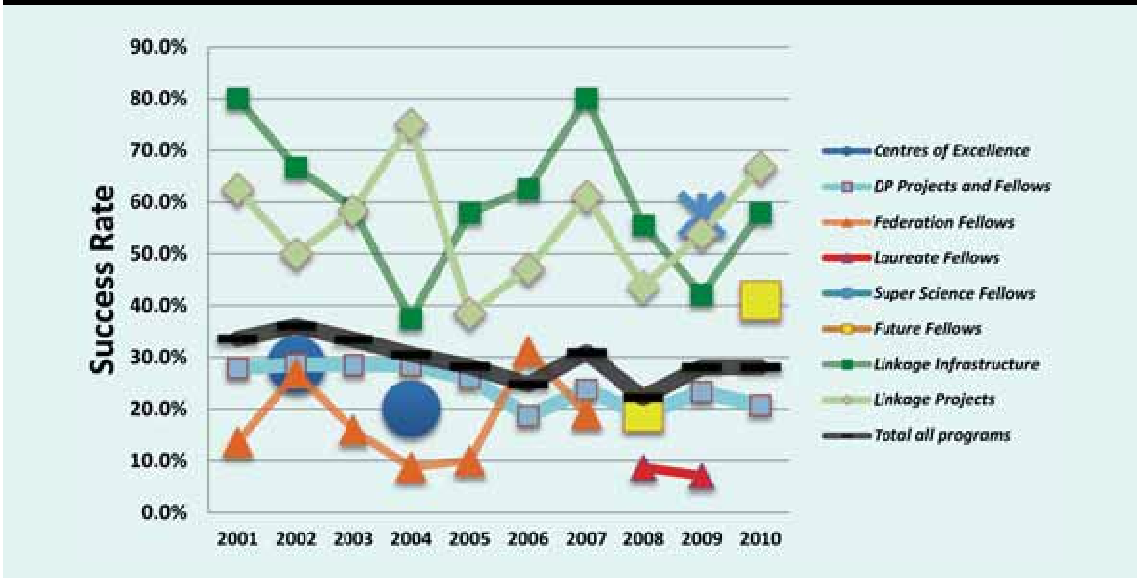


Figure 11: Success rate of physics applications to different ARC programs, 2001–10



managerial activities, a large part of which is due to onerous reporting requirements that are required by many funding agencies and the significant workload associated with preparing and submitting an ARC proposal.

Although most physics research is laboratory based, the maintenance and support staff required for larger research infrastructure is constantly under budgetary threat and therefore there is a risk of not being able to keep infrastructure to a standard that ensures that it is usable by the national and international research community. Similarly, budgets for subsequent upgrades are often not included in the planning stages for large infrastructure. This jeopardises the ability of Australian physics research to remain at the cutting edge of research and international collaboration.

Despite the Australian physics community's successful track record in high-quality research and technological outputs, research productivity is far from optimal due to high overhead costs of administration and high researcher effort required for preparation of funding applications for competitive grant schemes. This not only affects our local researchers, but also the international community with whom they collaborate given that over 60 per cent of funded Discovery Projects involved international collaborations (2011 round) [3]. In the 2009, 2010 and 2011 rounds approximately 4100 proposals were submitted in each year with 845, 925 and 931 proposals selected for funding respectively. Assuming on average two level D academics labour full time for two weeks to prepare these 4100 proposals then the total cost contributed by the community is about $54 million against the Discovery Project pool of $318 million in 2011. This cost does not include the substantial additional contributions from the large teams of expert administrators at the eligible institutions. Streamlining of the proposal preparation process would clearly make the community more efficient.

Moving to a 'white paper' system common in the USA could be one way of saving all this unproductive labour. In this system a short proposal is submitted, just a few pages, and these are assessed to select finalists who are invited to submit full proposals.

Time wasted preparing unsuccessful research proposals leads to an estimated 20 per cent productivity loss per active researcher (including administration time and cost, supervisor time etc.). This is a substantial productivity loss, particularly as 80 per cent of that productivity loss is not recaptured by accessing grant funds. The additional effort required to source matching funds that do not cannibalise funds required for other activities such as teaching or other research, results in attention being drawn away from research in progress.

3 www.arc.gov.au/pdf/annual_report_10_11.pdf

Critical issue 4: engaging in the international enterprise of physics

Australia is a well-integrated and highly regarded player in the international physics community, with Australian physicists collaborating with many international teams and addressing big research questions in physics. This level of international collaboration has enabled Australian physicists to capitalise on international investments made in existing research infrastructure that is often beyond the means of any single nation to build and maintain.

The Australian engagement with CERN has meant that we have been part of one of the biggest physics projects in our century. The live cross to the *2012 International conference on high energy physics* in Melbourne during the announcement of the discovery of the Higgs boson created enormous interest in physics in Australia. Australia also has significant engagement in the major astronomical observatories of the world and our participation in the Square Kilometre Array will continue that tradition. These and other engagements present opportunities for research staff and students to magnify their impact and learning. Opportunities are emerging with LIGO in the quest to observe gravity waves and ITER in the development of sustainable thermonuclear fusion power stations.

Coordinated effort and government support are necessary to establish and maintain research relationships with leading research organisations and nations, and to build and expand relationships with emerging nations.

Collaboration within the Asia–Pacific region is an increasingly important policy issue for Australia. Recent programs with China and India have complemented the technological strength and capacity of these nations, and strengthening of collaboration with these new partners is expected to add to the diversity of both disciplinary and cultural approaches in the Asia–Pacific region.

The Australian Academy of Science in a recent position paper to the Australian Government clearly outlined the rationale for increased investment in supporting internationalisation efforts. The recommendations included increasing the funding for collaborative innovation projects, for programs supporting early to mid-career researchers, and for building strategic partnerships. Furthermore, the Australian Academy of Science recommended investment in improved awareness campaigns, improved governance and improved diplomacy for Australia to adapt to future changes in the global scientific landscape. The physics decadal plan strongly supports the Australian Academy of Science's position paper on international science.

DECADAL OBJECTIVES

- Consolidate existing bilateral schemes and develop new schemes for international collaboration, including schemes to allow Australian researchers to become funded partners in US and EU initiatives
- Strengthen international collaboration with countries in the Asia–Pacific region, including China, India, Japan and Korea
- Make international research participation central to Australian physics.

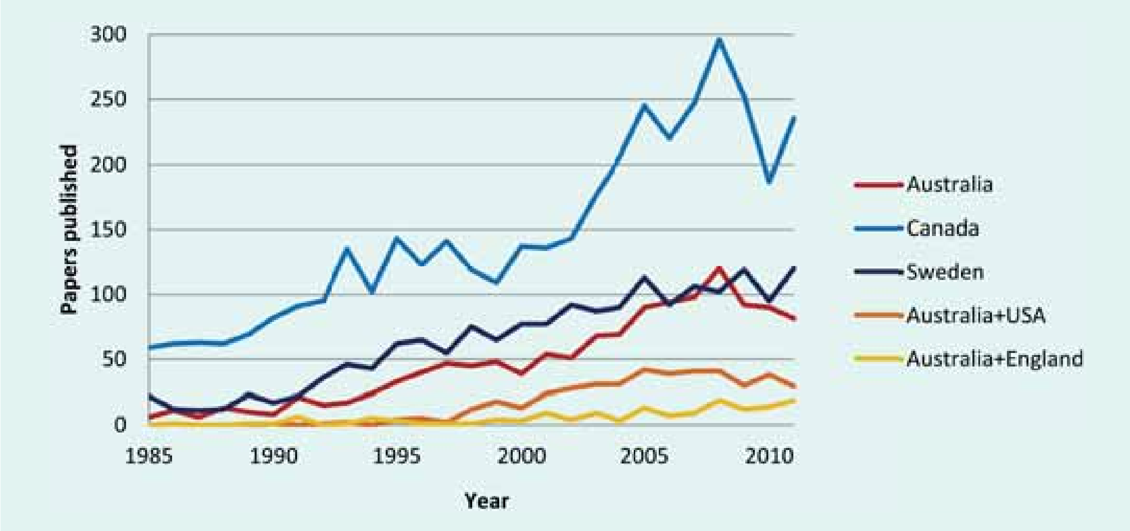
RECOMMENDED ACTIONS AND PATHWAYS

- Establish a replacement for the International Science Linkages scheme to enable access to major international physics facilities and research opportunities and to enable engagement with major overseas funding schemes such as the EU Framework Programs.
- Establish a replacement for the International Researcher Exchange Scheme that promotes two-way exchange at the level of individual researchers essential for rapidly developing fields.
- Ensure Australian physicists are able to provide inputs on international panels and agencies that develop international policy.

Australian physics in the international context

The international community's interest in the health of the Australian physics community is based on its ability to positively contribute to international debate

Figure 12: Annual number of papers in *Physical Review Letters* by country



and policy in a rational and scientific-evidence-based way. This requires that the standard of physics education from primary school to postgraduate education does not fall behind that of the remainder of the international community. It also requires that Australian physicists are able to provide inputs on international panels and agencies that develop international policy.

In the years since the 1993 review, a remarkable transformation has swept through Australian physics. There has been a steady rise in the number and percentage of publications with Australian authors in the international journals. This most likely reflects a greater engagement with the international community and also the increasing importance of publications in charting the progress of projects and careers. For example, measured by publications in *Physical Review Letters*, the fraction of papers with Australian-domiciled authors has steadily risen from less than 1 per cent per year to close to 3 per cent per year. At the same time, global trends have seen the rise of internationalism. In a study commissioned by the Royal Society titled *Knowledge, networks and nations* [1] it was shown that the proportion of the world's papers with more than one international author has steadily increased since 1996 from 25 per cent to over 35 per cent. Today, over a third of all articles published in international journals are internationally collaborative, up from a quarter 15 years ago. This is also true in Australia as can be seen by the papers that feature traditional co-authors from the USA and England. However, this is not the full story, since this fraction of papers accounts for only about half of the total in each year. Perhaps the start of the ARC system [2] in 1988 for supporting research was also an important contributor to this trend.

In July 2002 the ARC commissioned a submission [3] to the National Research Priorities Taskforce to make the case that Australia can and should aspire to develop a national research and innovation system that is characterised by attributes that include the following:

- Australia will be a preferred location for economic investment in new ideas by companies from around the world — it will be an important hub within innovation networks that span the globe
- Australia will be a preferred location for world-class researchers to pursue their work and careers
- Australia will be a preferred site for developing major infrastructure to house and equip teams from around the world engaged in research programs at the frontiers of global knowledge
- Researchers in Australia will have strong links to cutting-edge international research programs and ready access to state-of-the-art research facilities and equipment in other countries
- Australia will be a preferred training location among the best young researchers from around the world.

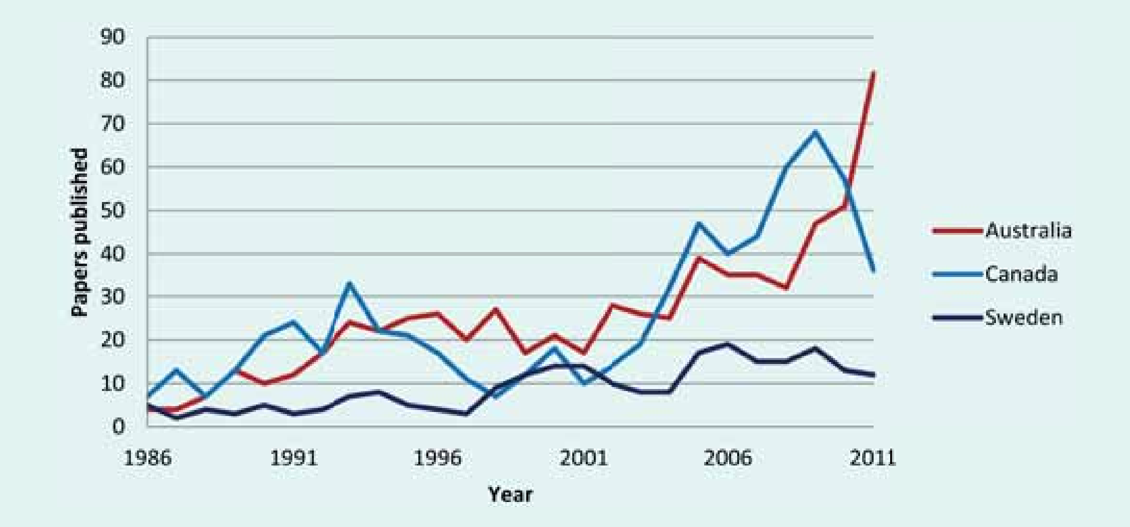
The submission suggested that by the year 2020, Australia can meet a number of ambitious but achievable targets such as:

1 royalsociety.org/policy/reports/knowledge-networks-nations/

2 www.arc.gov.au/general/history.htm

3 www.arc.gov.au/pdf/ARC_priorities_submission.pdf

Figure 13: Annual number of papers in *Optics Letters* by country



- Twenty Nobel Prizes in physics, chemistry, physiology or medicine, and economics
- An ongoing, structural net gain of researchers of the highest international standing
- A leadership role in major international consortia in five areas of research, undertaking programs at the boundaries of global knowledge
- The establishment in Australia of five major collaborative research facilities by the international community
- The establishment of five major national innovation clusters characterised by rapid and extensive technology transfer via spin-off company formation and licensing of intellectual property
- An ongoing, structural increase in the numbers of high-quality students choosing to undertake research training in Australia.

These attributes and goals are strongly endorsed by the physics decadal plan and are consistent with the recommendations. The major challenge will be to develop a strategy for achieving these goals. There is no doubt that substantial funding will need to be a major element of this strategy. The analysis by Frank Larkins of the generously funded ARC Federation Fellowship scheme, which had similar goals to the ones stated here, reveals the challenge of 'attracting international research talent' which 'highlights the very competitive nature of the worldwide quest for intellectual capital' [4]. It is also likely that deep and long-standing relationship building [5] will need to be developed before approaches are made to attract international research talent. Hence support for bilateral relationship building is essential if these goals are to be achieved.

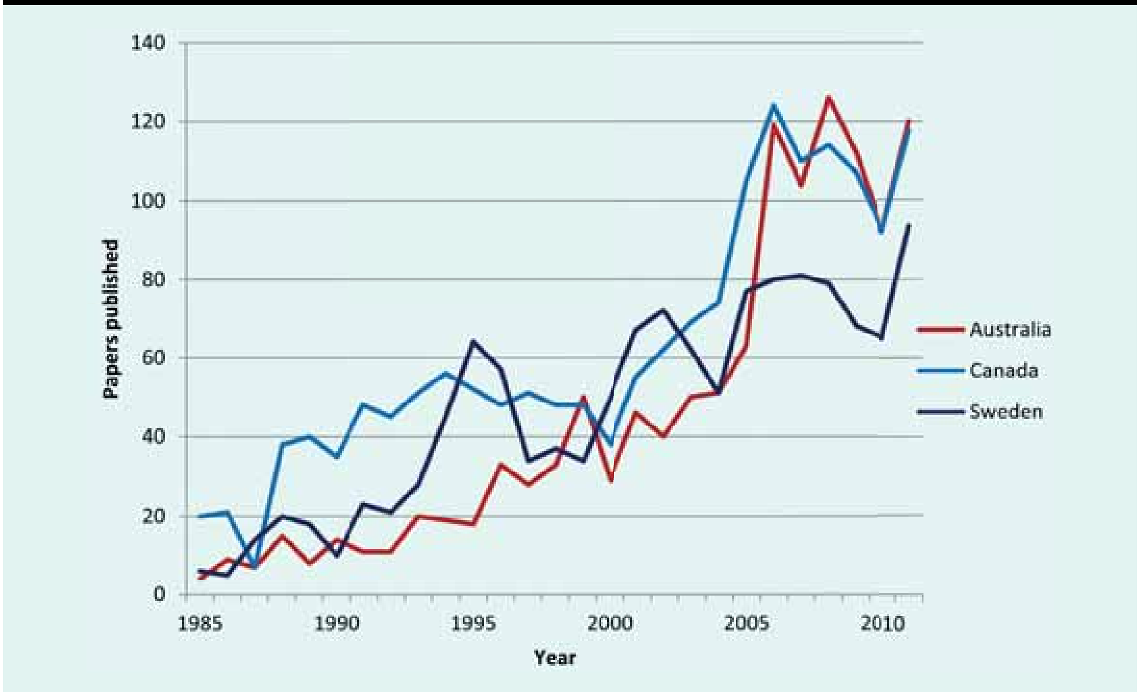
Historically, the USA has been the world leader in scientific research publications and outputs, a trend that continues today. However, whilst three decades ago scientists from the USA produced almost 40 per cent of the publications in journals indexed by Thomson Reuters in the *Web of science*, in 2010 the share of publications became more evenly spread globally with only 29 per cent of papers having US co-authors. Nations from the EU increased their share of research papers to 36 per cent of global publications, surpassing the USA in the mid-1990s. The Australian share of global publications has been growing steadily from 2.9 per cent in 1999 to reach 3.2 per cent in 2008 with the volume of Australian publications rising annually by an average of nearly 5 per cent, and reaching over 36,000 publications in 2008. This growth is higher than that of other selected OECD countries and of world, OECD and EU-27 publication averages. Furthermore, in the *2010 Australian innovation system report*, the impact of Australian physics in terms of the relative citation index is the highest for all science disciplines [6]. The relative citation index takes into account the variation in discipline citation rates as it divides the Australian citation rate by that for the rest of the world, and hence is a good measure of relative discipline performance. Tracking of the Australian publications record in three of the most important global scientific physics journals in comparison with countries of similar size, shows that Australian physics has increasing impact and that there is also a slowly

4 FP Larkins *Australian higher education research policies and performance 1987–2010*. MUP 2011

5 R Sloggett, private communication

6 *Australian innovation system report 2010* www.innovation.gov.au/Innovation/Policy/Pages/AustralianInnovationSystemReport2010.aspx

Figure 14: Annual number of papers in *Applied Physics Letters* by country



increasing trend towards collaborative publications with researchers in the USA and England (figures 12–14).

Currently, Australia's international collaboration is predominantly with North America, Europe and the UK. Collaboration with the Chinese Academy of Science is increasing, but research collaborations with other emerging nations are currently not as well established. The globalisation and internationalisation of research leads to fierce competition for attracting international talent in all physics sub-disciplines worldwide, from which the USA benefits most due to its ability to attract world-class scientists from most countries. It is the predominant research destination for researchers from all global regions. For example, the USA is the most important research collaborator for India, whose research productivity is expected to overtake most G8 nations between 2015 and 2020 [7]. In comparison, Australia is only India's ninth most important research partner based on research publication output, despite the fact that our research capabilities complement India's technological capacity.

Thompson Reuters expect collaboration within the Asia–Pacific region to become an increasingly important policy issue for Australia. Collaboration with China and India is particularly important, as the Australian research competencies complement the technological strength and capacity of these nations.

Strengthening of collaboration with these new partners is expected to add to the diversity of both disciplinary and cultural approaches in the Asia–Pacific region and could lead to increased challenges to traditional research relationships. However, within physics there are some impediments to internationalisation of research. These include a lack of evidence of clear international collaboration strategies and roadmaps, and a lack of bilateral schemes and formal agreements with other countries, including with Asian research agencies and countries. Existing constraints related to achieving critical mass in individual institution student numbers in teaching advanced programs, for example in theoretical physics, at a norm that is comparable with international standards, make it difficult to achieve international impact across some of the physics sub-disciplines.

The importance of maintaining existing research relationships with leading research organisations and nations, and also of building and expanding research relationships with emerging nations requires that effort must be coordinated and government support provided to establish these relationships without losing research productivity through diverting effort away from research.

The Australian Academy of Science in a recent position paper to the Australian Government [8]

7 Thompson Reuters: *Global research report India* October 2009

8 Australian Academy of Science, *Australian science in a changing world: innovation requires global engagement*, November 2011

clearly outlined the rationale for increased investment in supporting internationalisation efforts. The recommendations included increasing the funding for collaborative innovation projects, for programs supporting early to mid-career researchers, and for building strategic partnerships. Furthermore, the Academy recommended investment in improved awareness campaigns, improved governance and improved diplomacy for Australia to adapt to future changes in the global scientific landscape.

FINDING BURIED ORE BODIES WITH SUPERCONDUCTING SENSORS

Deeply buried deposits of minerals such as nickel, gold and silver are of great interest to the mineral industry because most ore found to date has been on or just below the surface. However, these deposits can be hard to find because conventional coil magnetic sensors are not sensitive enough. In Australia, exploration for these minerals is even more difficult because the overburden (material above the deposit) is often highly conductive.

CSIRO's LANDTEM™ is a highly portable exploration tool which can spot the difference between ore and conductive overburden, even when the ore body is deeply buried. LANDTEM™ uses highly sensitive magnetic sensors known as SQUIDs (Superconducting QUantum Interference Devices). LANDTEM™ is helping unearth large deposits of nickel sulphide and silver worth hundreds of millions of dollars.

It has also:

- found several previously undetected large nickel sulphide deposits in Western Australia
- cut exploration costs by 30 per cent to a company working in difficult terrain in northern Quebec in Canada
- clarified data at BHP Billiton's Cannington silver mine in Queensland.

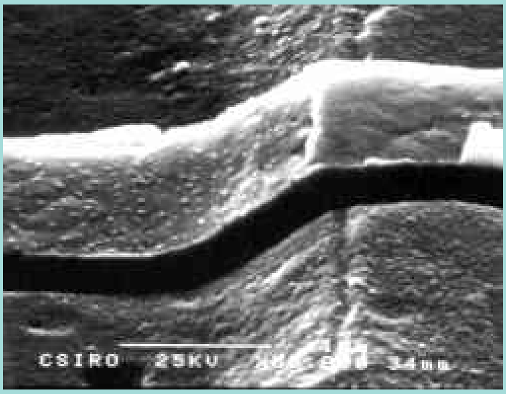


IMAGE: CSIRO MATERIALS SCIENCE AND ENGINEERING

DAVID MILLS AND AUSRA: SOLAR POWER GENERATION — FROM THE UNIVERSITY OF SYDNEY TO CALIFORNIA TO FRANCE AND BACK TO AUSTRALIA

A media release by AREVA, a France-based multinational carbon-free power generator company, reads: 'AREVA Solar has been awarded a major contract to install a 44 megawatt solar thermal augmentation project at a 750 megawatt coal-fired power station in Queensland, Australia, representing the largest solar project in the Southern Hemisphere and the world's largest solar/coal-fired power augmentation project. AREVA Solar's Australian-pioneered Compact Linear Fresnel Reflector (CLFR) Technology will be installed at CS Energy's Kogan Creek Power Station. Construction of the solar boost project is scheduled to begin in the first half of 2011, with commercial operation planned for 2013. The AU$104.7 million Kogan Creek Power Station Solar Boost Project represents the largest deployment of AREVA's solar thermal technology in the world and will generate an additional 44 000 megawatt hours of electricity a year'. 'By using energy from the sun with AREVA's solar booster application, we will make the coal-fired plant more fuel-efficient and reduce its greenhouse intensity — avoiding the production of 35 600 tonnes of greenhouse gas emissions annually' says AREVA. The project will create 120 jobs during the construction period.

The principle of CLFR technology is very simple and can be used in a variety of industrial applications including enhanced oil recovery, petroleum refining and food processing. Rows of flat mirrors that follow the path of the sun are arranged in a one-square-mile grid. The mirrors reflect the sun's heat onto water-filled pipes

DAVID MILLS AND AUSRA... (CONTINUED)

above, creating steam that cranks a turbine in a nearby power plant. The electricity produced does not produce a molecule of greenhouse gas. Unlike photovoltaic or other concentrated solar technologies, which lose output immediately when clouds come over, the technology has 20 to 30 minutes of stored capacity, so it can adjust to weather changes or other factors affecting the electric grid.

The CLFR technology of this power plant has been invented by Dr David Mills who has been working in non-imaging optics, solar thermal energy, and photovoltaic systems for over 32 years.

Dr Mills graduated with a Bachelor of Science in Physics and a PhD in non-imaging optics from the University of New South Wales. He proceeded to lead the Solar Energy Group in the School of Physics at the University of Sydney that developed and licensed the evacuated-tube solar water heater technology, which comprises 60 per cent of the world's solar collectors. Dr Mills originated and ran the research program that in 1991, with colleague Dr Q-C Zhang, developed the most advanced sputtered double cermet selective absorber coating, which is now used in evacuated tube receivers by China's largest solar company, Himin. He developed or co-developed other commercial systems including the Prism solar concentrator (Sol X) and the 'S' evacuated tube reflecting system (Solahart). A solar sterilizer design he originated won a World Health Organization award in 2002, and he was a finalist in the 2002 World Technology Awards for Energy.

Dr Mills and a friend, a professor of engineering at the University of New South Wales, formed a company and invested their own money to cover the patents for the CLFR technology that they had purchased for very little money from the University of Sydney. The patent costs of $80 000 were initially paid out of their personal funds, which was a financial hardship at the time. However, they had faith in it and eventually got a grant from the government.

In 2002 Dr Mills and his company built a small 1.5 MW demonstrator solar power station in New South Wales next to the coal-fired Liddell power station in the Hunter Valley. It was the first of its kind ever built commercially in the world. At the time, investors in Silicon Valley were looking for solar projects because of the incentives that had been put out by the government there. Eventually Dr Mills made an initial deal for $43 million and started a new company in the USA, Ausra, which bought these shares in the Australian company.

The group of investors that invested in Ausra were from the USA, Canada, the UK and Starfish in Australia, and they all looked very closely at the value of what they obtained from this deal and what it might develop into.

Over time the company got additional investment of more than US$130 million and was able to employ very good research and development and engineering staff from the San Francisco Bay area and elsewhere, using people from Stanford University, University of California Berkeley and the Massachusetts Institute of Technology. They were able to make a lot of engineering progress on the design, and also a lot of ideas-based product progress as well. Dr Mills states that this could have been done in Australia also, in principle, as there are very good people here but that the high level of money just wasn't available to pay for it. In the company in the USA there were two mathematicians, plus physicists, plus engineers working together and there was basic work going on at any stage in the research and development department.

In February 2010 the French conglomerate AREVA announced a 100 per cent acquisition of Ausra. This acquisition launched AREVA's new global solar energy business and reflects AREVA's strategic objective to be the world leader in concentrated solar power and its push into diversification in its renewable energy portfolio of wind and biomass power generation.

Now, AREVA has won the contract for Australia's largest solar plant in Queensland, so the CLFR technology is actually returning to Australia with the construction of this plant.

CSIRO'S PLASCON™ WASTE DESTRUCTION SYSTEM

The PLASCON™ waste destruction system developed by CSIRO and Siddons Ramset Pty Ltd uses an arc plasma (like that used in arc welding) to destroy such substances as:

- fluorocarbon greenhouse gases
- toxic organic chemicals such as polychlorinated biphenyls (PCBs)
- ozone-depleting substances such as chlorofluorocarbons (CFCs) and halons (bromochlorofluorocarbons), which were once used as fire extinguishers.

The development of the PLASCON process required an intensive research and development effort that involved physicists (for both experiments and computational modelling), chemists, and electrical, chemical and mechanical engineers. The lead scientists in CSIRO were Dr Tony Murphy, Dr Tony Farmer and Dr Trevor McAllister.

There are currently twelve PLASCON units around the world:

- two at Nufarm in Melbourne, Victoria, destroying waste liquid from the production of the herbicide 2,4-D
- one at the Australian National Halon Bank in Melbourne, Victoria, destroying Australasian stockpiles of halons and CFCs
- one at BCD Technologies in Brisbane, Queensland destroying PCBs and insecticides
- one originally installed at DASCEM Europe's plant in the UK to destroy Europe's stockpile of halons and then transferred to Mexico's Quimobasicos company where it destroys trifluoromethane; it has recently been joined by a second unit
- one at Honeywell Specialty Chemicals, Louisiana, USA, destroying fluorocarbons
- four at Mitsubishi Chemical Company in Japan, destroying the company's stockpile of PCB-kerosene mixtures
- one in Ohio, USA, destroying halons.

The case of trifluoromethane is particularly interesting. Trifluoromethane is a greenhouse gas formed as a by-product of hydrochlorofluorocarbon production. Hydrochlorofluorocarbons are CFC replacement chemicals that are being phased out in the developed world, but whose use is permitted until 2040 in the developing world. Until recently, trifluoromethane was released into the atmosphere. However, under the Kyoto Protocol, carbon credits can be paid to developing countries for projects that reduce greenhouse emissions.

Trifluoromethane has a global warming potential 11 700 times that of carbon dioxide (CO_2). At A$20 per tonne of CO_2, the rate per tonne of trifluoromethane is well over A$200 000. This exceeds the cost of destruction by more than a factor of twenty and PLASCON™ destroys about 185 tonnes per year. Destroying this much trifluoromethane is the equivalent of removing the CO_2 emissions of a 300 megawatt coal-fired plant or 500 000 cars each year.

Conclusions

The laws of physics and their applications shape the fabric of society — the way we communicate, travel, receive health care, in short, the way we live our lives. Australian physicists have played a substantial role in contributing to this knowledge and application of these principles. This decadal plan seeks to understand how these valuable contributions can continue to underpin Australia's future.

The physics community is defined as a number of stakeholder groups: secondary schools, higher education, researchers, industry and business, the government, and domestic and international communities. Each of these groups has an important role in the physics innovation system and those roles are acknowledged here. The strongest signal the Decadal Plan Working Group received from these stakeholders was concern about physics education. A substantial opportunity exists to improve the quality of physics education in schools through better training and support for teachers. Capitalising on this opportunity will have a very high likelihood of benefitting all of the other stakeholder groups, as well as ensuring excellent physics outcomes for future generations. Particular attention should be paid to Indigenous and gender inequalities.

Despite the concerns about secondary school physics education, undergraduate training is well subscribed with excellent faculty and programs that continue to attract international as well as domestic students. This success provides further support for the strategies outlined to improve secondary school physics education. The present strength of our tertiary physics education system is a consequence of our strong research performance. The crossover of talent from research into university teaching engages and inspires students.

The research community is a beacon of success in Australian research, although true measurement of outputs from the physics community is likely understated due to the inter-relationship of physics with other disciplines. The ARC Centre of Excellence program has been well suited to support physics research and pursuing similar funding schemes is a high priority to maintain the research sector's high level of performance.

Industry and business are vital parts of the overall physics community and there are numerous latent opportunities that may be realised by greater interaction between this sector and academic researchers. The anticipated gains are expected to be shared mutually and include greater commercialisation success and superior innovation through the intermingling of pure and applied research endeavours.

The government and community sectors are daily users of the outputs from the physics community. In our market force economy, these actors play an important part in defining demand. The discipline stands to gain from appropriate promotion of physics to these stakeholders and in particular encouraging the public to engage with how physics shapes our daily lives and its potential for future developments.

The roadmap outlined in this decadal plan comprises specific recommendations for:

- achieving a physics-literate workforce and community
- realising human capital in physics
- building on physics research investment
- engaging in the international enterprise of physics.

The interconnectedness of the various sectors of the physics community increases the complexity of implementing the recommendations in this plan; however, this also provides significant opportunity to embrace engagement between the different sectors and thereby foster a productive physics community with strong engagement with the international community.

Australia has long been the beneficiary of the industry and innovation propelled by the Australian physics community. This decadal plan strives to secure this role of physics in underpinning Australia's future. With continued support from the Australian government and through strengthened interdisciplinary and international relationships the Australian physics community will have the ability to embrace the opportunities available to it and thereby maintain its position as a player in the global physics community. This in turn will enable Australia to capitalise on future discoveries and be a nation where excellent scientists choose to live and work.

THE IMPORTANT ROLE OF THE NATIONAL COMMITTEE FOR PHYSICS

An effective plan needs an effective implementation strategy.

After considerable discussion with key stakeholders it is proposed that the physics decadal plan be overseen by the National Committee for Physics of the Australian Academy of Science. The committee will be charged with specific responsibility for the development of strategies to implement the recommendations in the plan. Inspiration for this proposal has been provided by the Wentworth Group of Concerned Scientists [1], which is an independent group concerned with advancing solutions to secure the long-term health of Australia's land, water and biodiversity, and the National Committee for Astronomy, which has had custody of the development of the strategic plan for astronomy in Australia.

1 www.wentworthgroup.org/

The brief to the National Committee for Physics is to:

- develop strategies to recruit and train more inspirational physics teachers for Australian Schools
- pursue internationalisation strategies for physics research
- drive creative thinking in physics from discovery to application
- engage business, community and political leaders in the use of physics to guide decisions of national importance
- sustain dialogue between different domains of the physics community in Australia
- build capacity by mentoring and supporting early-career physicists and developing their understanding of public policy.

This will keep the plan alive for the next decade.

Acknowledgements

The key contributors are acknowledged below, and they are thanked for their commitment and dedication to completing this huge and important work.

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Michelle Simmons FAA, University of NSW (Chair)

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FINANCIAL SUPPORT

Australian Research Council: Linkage Learned Academies Special Projects (LASP) Scheme

Australian Academy of Science

Australian Institute of Physics

We also thank the many people — students, teachers, scientists and experts from many disciplines, backgrounds and industries — who generously provided their time, thoughts and inputs into the process of developing the plan.

RESPONSES TO WHITE PAPER AND EXPOSURE DRAFT

Joe Wolf, Michael Morgan, Bruce Hartley, Brian Kennett FAA, Igor Bray, Steven Prawer FAA, Robert Robinson, Maryanne Large, Adam Edwards, Aidan Byrne, Victorian Branch Education Committee, Anthony Williams, Matthew Hole, Klaus-Dieter Liss, Chris Kaczan, Bob Frater FAA, ACT Branch of the Australian Institute of Physics, Dan O'Keeffe, Elaine Sadler FAA, Adi Paterson, Jacqueline Davidson, Jim Williams FAA, David Blair, Marc Duldig, Bruce McKellar FAA

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Ruth Drinkwater, BSc, MBA, CEO of Australian Association of Angel Investors, Director of Women in Technology; Prof Andrew Dzurak, BEng, PhD (eng), Director of UNSW's Semiconductor Nanofabrication Facility, Node Director Australian National Nanofabrication Facility, NSW Node Manager ARC Centre of Excellence for Quantum Computer Technology, Scientia Professor UNSW 2010, Electrical Engineering University of New South Wales; Elizabeth Ebert, PhD (meteorology), Research Meteorologist, Centre for Australian Climate and Weather Research, Australian Bureau of Meteorology; Natascha Eckert, MBA, Siemens, Munich, Germany; Prof Ben Eggleton, BSc (physics), PhD (physics), Director ARC Centre for Excellence for Ultrahigh-bandwidth Devices for Optical Systems (CUDOS), Prime Minister's McIntosh Prize for Physical Scientist 2004, Scopus Young Researcher of the Year Award 2010; Peter Fisk, BSc (physics), PhD (physics), General Manager Physical Metrology, National Measurement Institute; Cathy Foley, BSc (physics), DipEd, PhD (physics), Acting Chief, CSIRO Materials and Engineering, President FASTS; 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Prof Edwin van Leeuwen FTSE BSc (mathematics & theoretical physics), PhD (mathematics), Clunies Ross Prize for contributions to exploration geophysics, Centenary Medal for Services to the Australian Society in Research and Development, formerly Global Manager Exploration and Mining Technologies at BHP, currently Managing Director Norilsk Nickel, WA ; Russel Lesley, BSc (physics), Australian Safeguards and Nonproliferation Office; Melissa Makin, BSc (physics), PhD student, University of Melbourne; Steven Meikle, BApplSc (physics), PhD (biomed eng), Head of Imaging Physics Laboratory, Brain and Mind Research Institute, University of Sydney; David Mills, BSc (physics), PhD (physics), formerly CEO of Ausra; Prof Tanya Monro FAA, BSc (physics), PhD (physics), ARC Federation Fellow, 2008 Prime Minister's Malcolm McIntosh Prize Physical Scientist of the Year, Director Centre of Expertise in Photonics, School of Chemistry & Physics, University of Adelaide; Garry Newsom, BSc (mathematics), PhD (mathematics), DSTO; 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Institute, School of Physics, University of Melbourne; Prof Anatoly Rozenfeld, MSc (physics), PhD (nuclear physics), Director Centre of Medical Radiation Physics, School of Engineering Physics, University of Wollongong; Christine Scala, BSc (physics), PhD (physics), DSTO; Len Sciacca, Chief Operating Officer, DSTO; Jesse Searl, Managing Director, Poseidon Scientific Instruments, Freemantle; Mia Sharma, BSc, DipEd, NSW Scientist of the Year for Leadership in Teaching Secondary Science 2010, Head of Science, International Grammar School, Ultimo NSW; Prof Margaret Sheil, BSc (chemistry), PhD (chemistry), CEO of ARC; Dr Sam Silicia, BSc (physics), PhD (physics), Chief Investment Officer, HostPlus Superannuation Fund; John Soderbaum, BSc (physics), PhD (physics), Executive Director, Acil Tasman Canberra; Associate Prof Marion Stevens-Kalceff, BSc (physics), PhD (physics), Deputy Director UNSW Electron Microscope Unit, School of Physics, University of New South Wales; Noreen Summeth, Science Teacher Teesdale Primary School, Victoria; Prof Doreen Thomas, BSc (mathematics), Acting Dean Faculty of Engineering, University of Melbourne; Chris Walton, APESMA; Prof Jo Ward, BSc (chemistry), PhD (chemistry), Dean Faculty of Science, Faculty of Science and Engineering, Curtin University; Drew Williams, BEc, LLB, Aragon Capital; Prof Bob Williamson AO FAA FRCPA FRS Member Royal College of Physicians London, Honorary Doctor of Medicine, Human Genetics, University of Melbourne; Chris Wood, BSc, PhD (physics) VP Santa Fe Institute, Santa Fe, USA.

Appendix 1
Presentation of the plan process: site visits

2011

Griffith University	6 May
Queensland University of Technology	6 May
University of Queensland	6 May
Macquarie University	26 May
University of Sydney	26 May & 1 June
University of New South Wales	26 May
University of Newcastle	22 June
University of Adelaide	1 July
Defence Science and Technology Organisation, Adelaide	1 July
University of Melbourne	21 July
Australian National University	5 September
Science and Technology Australia	5 September
Monash University	3 November
CSIRO Linfield	19 December
ANSTO Lucas Heights	19 December

2012

Curtin University of Technology	7 May
University of Western Australia	7 May

Appendix 2
The physics decadal plan process

This physics decadal plan — *Building on excellence in physics: underpinning Australia's future* — is the product of a year of intensive work involving the Australian and international physics community to survey the discipline of physics in Australia and identify opportunities for the next decade.

The plan development process was managed by the Physics Decadal Plan working group under the auspices of the Australian Institute of Physics and the Australian Academy of Science. Financial support was provided by the Australian Research Council, the Australian Academy of Science, and the Australian Institute of Physics.

Large cohorts of physicists serve the nation in academia and government, in education and in industry. The decadal plan is an attempt to survey the views of this community. The working group commissioned a series of interviews with individuals from all branches of the discipline, piecing together a picture of where we find ourselves today, our potential for the future, and impediments to achieving that potential. In addition, submissions were solicited, received and analysed. Feedback was provided through the decadal plan website and from numerous face-to-face meetings around the country. Inspiration was sought from several cognate decadal plans and the pioneering work of the 1993 physics decadal plan committee.

There were four components to the formulation of the decadal plan. These were:

- background stakeholder sector research
- consultation with the physics community
- analysis and development of recommendations on the basis of this information
- promotion of the plan process.

The background research focused on the current state of physics in Australia. Relevant publicly available information on the external operating environment of physics, on global and national trends in physics, and on the current performance of the major sectors that make up the 'physics community' were compiled and analysed.

The physics community was consulted in various ways, including by targeted interviews, 'town hall meetings', and invitation for submissions via the decadal plan website. The interviews provided information on the general state of physics and the physics community in Australia in the context of the global and national operating environment. They described the current issues and systemic problems that are experienced by the physics community as a whole and provided a prioritised set of general requirements for addressing these systemic problems.

The analysis of global trends, weaknesses and threats identified opportunities that will allow the physics community to use its strengths to strategically position physics for the next decade and beyond. This phase included workshops to agree about the strengths to build on, the weaknesses to eliminate and the gaps and limitations that need to be overcome. The outcome of this strategic planning process was a number of recommendations for proposed implementation.

The process was promoted to the physics community through several channels including:

- AIP Physics Congresses in 2008 and 2010
- an update in each AIP newsletter that is delivered electronically to the AIP membership
- encouragement of each of the interviewees to promote participation in the plan development process through their specific affiliations, via professional newsletters, media and other contacts
- individual presentations from the Chair and members of the Physics Decadal Plan working group to physics departments and to other organisations such as, for example, CSIRO, DSTO, universities and other interested groups
- the physics decadal plan website, which was used to keep the stakeholder community up to date with the process and the submitted and produced materials.

Table 7: Critical success factors for a thriving, productive and effective physics community	
Contributors to the physics landscape	**Critical success factor (CSF)**
Primary schools	Teacher training to include a strong science and maths components; ongoing support and teaching resources that are age appropriate
Secondary schools	Trained physics and maths teachers (trained at three years higher than the level they teach) & appropriate infrastructure/resources; students interested in studying physics at school; students aware of the relevance, applications and career opportunities in physics
Higher education	Students who are appropriately qualified wanting to study physics in Australia; related disciplines motivated to source physics service teaching from physicists; excellent and inspiring physics teaching
Research	Vibrant research community that generates new ideas; excellent research infrastructure and resources to attract research talent; predictability of funding to attract and retain talent and take research risks that don't depend on short-term funding cycles
Funders	Return on investment (relative to other investment options)
Government	Improved productivity/economic wealth, employment, country competitiveness attributed to funding; improved international status; improvement in national capabilities and expertise
Industry	Access to IP that improves competitiveness and profitability; trained future employees; access to research assets that they wouldn't buy themselves/contract research capacity; favourable conditions for operations in the country
General public	Knowledge to better participate in current debates, benefit of applied IP (to society), education for their children; understanding of the Universe (origin, evolution and fate!)
International community	Access to expertise, collaboration, leverage of their capabilities; ability to address bigger questions that can't be solved in isolation; access to high-quality education & research training

The critical success factors for a vibrant physics community

The critical success factors for Australia to become more successful and globally competitive in physics education, research and development, to create a knowledgeable population and economic wealth are listed in table 7.

A thriving, productive and effective physics community requires that each sector understands and contributes to the achievement of each other's critical success factors. It also requires that each sector understands the customer-supplier relationships within the whole physics community and the rules by which each of them operates.

The current operating environment of physics in Australia

Although secondary and desk-top research both provide valuable information, this information is often not current and may not accurately reflect the immediate experiences of the physics community.

To identify the current strengths, weaknesses and operating constraints within the physics community, 65 in-depth interviews were conducted. The research method followed a slightly modified approach of Burchill and HepnerBrodie [1] that was developed for new product and service solution development. This approach is used in industry and business to rapidly determine the key requirements that need to be addressed to enable sustained competitive advantage in the market place. The process enables the identification of problems and constraints in the operating environment and of the requirements that must be met for the community to be functional, effective and competitive in the future.

The findings from the interviews of the Australian physics community showed that there are many common factors between the sectors of the physics community in terms of identified issues and operating constraints.

The physics education sector's two 'legs' — school and higher education — are highly interdependent in terms of the competency of science and physics teachers and their effect on both the attitude and capabilities of school students which in turn affects

1 G Burchill and C HepnerBrodie, *Voices into choices*. Center for Quality of Management (Cambridge, Massachusetts), Joiner Associates 1997

the number and capability of each year's new cohort of tertiary physics students.

The tertiary education sector on the other hand influences the attitude of physics students towards careers other than research, such as teaching, and strongly influences the quality of teacher education. Shortcomings in either of these components of the education system are perceived to have a severe detrimental domino effect on the capabilities of other sectors of the physics community, the general science literacy of the public and on Australia's economy. Constraints in these two sectors are seen as equivalent to turning on a tap that has the potential to irrigate fertile fields, but instead delivers a mere trickle of muddy water.

The physics community generally agrees that the research sector has the highest influence on the technology supply chain in terms of the quality and impact of their main outputs of knowledge, graduates, postgraduates trained in research processes, and intellectual property that can be used by industry and business. Investment in fundamental and basic research is seen by all sectors of the physics community as being an essential indicator of an 'intelligent' and 'clever' country with scientists that are able to compete on the world stage. That breakthroughs in knowledge only occasionally lead to commercialised technology applications is not seen as something that should impact on the value and merit of undertaking and funding fundamental research.

The physics community is generally perceived to have conservative approaches to many aspects of research, education and industry interaction, which makes engagement between the sectors challenging. The perceived remoteness of the higher education and research sector from the rest of the physics community was believed to be mirrored by the similarly conservative processes of major funding agencies.

The impact of this doubly applied conservatism is seen as stifling the emergence and funding of the 'large ideas' that are needed to keep Australia at the forefront of research in the global context, and also for the continued competitiveness of Australian industry that relies on inventions to emerge from Australian higher education and research.

The key features of the current Australian physics operating environment are that:

- Physics is a major contributor to the global research competitiveness of Australian research providers — some of the capabilities are world class.
- There is a lack of understanding of the contribution of physics to society — specialist teaching is limiting interest in physics in schools.
- Job security is a major problem for retaining talented researchers in academia and in research institutions.
- The academic research sector is currently inwardly focused.
- Employment opportunities exist for graduates outside academia, but are difficult to match up.
- Translation of research outputs into technology through commercialisation is a major problem area.
- Administrative and funding processes are negatively impinging on research efficiency and productivity.

The findings of this process are presented in Part 2 of the physics decadal plan which is available on the website (see inside front cover).

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