# Nanotechnology in Australia

## Trends, applications and collaborative opportunities

December 2009

Australian Academy of Science

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# Contents

# Foreword

Nanotechnology is already having a profound impact upon major industries world wide, including at the very least electronics, computers, communications, defence, energy, biomedical, transport and manufacturing. Nanoscale science and technology is multidisciplinary, involving physicists, chemists, biologists, materials scientists, chemical, mechanical and electronics engineers and medical scientists. Interactions between researchers, innovators and businesses are critical to the progression of nanotechnology from research and development to application and commercialisation.

The Academy appreciates the steering and guidance of this project by three of its Fellows who are leading experts in their field of nanotechnology, Professors Chennupati Jagadish, Frank Caruso and Gordon Wallace. The keynote address at the Nanotechnology Stakeholder Day by Professor Jackie Ying of the Singapore Institute of Bioengineering and Nanotechnology provided valuable insight into her institute's experiences in developing nanotechnology into commercial outcomes. The Academy also thanks participants in the survey and attendees of the Nanotechnology Stakeholder Day for their contributions to this project. Special acknowledgement is given to the Australian nanotechnology networks – the Australian Research Council Nanotechnology Network, the Australian Nanotechnology Business Forum and the Australian Nanotechnology Alliance – for their assistance in distributing and promoting awareness of the survey to their nanotechnology communities.

This research project was coordinated and managed by Academy Project Officer Dr Fiona Leves. The ARC is gratefully acknowledged for its financial support under the Learned Academies Special Projects Scheme.

We hope this report and its recommendations will inform Australian Government consideration to ensure that Australia benefits from the transformational capacity of the emerging science of nanotechnology.

Professor Kurt Lambeck AO
Academy President

# Executive summary

## Australian nanotechnology in 2009

Nanotechnology has emerged as a critical field with the potential to impact nationally significant issues as diverse as health, water and energy. Given the importance of nanotechnology to Australia's future it is necessary to characterise Australia's current research capacity and capabilities. This was achieved through the completion of a series of quantitative and qualitative research activities during 2009, funded by an Australian Research Council (ARC) Learned Academies Special Projects grant.

International benchmarking using bibliometrics indicated that Australia is improving its position relative to other countries but that there is still work to be done in order for Australia to achieve world averages. Bibliometric data also indicates that Australia's collaboration partners changed in the last decade, with China now Australia's second most frequent partner by publication.

During mid-2009 the Australian Academy of Science distributed a survey amongst Australia's nanotechnology community that examined research trends and collaborations. The data indicates that nanotechnology is strong across a variety of fields but is mostly at the earliest stages of development (basic and applied research). Collaborations are almost equally distributed between Australian and international partners, and are most likely to involve the exchange of ideas, data and/or joint publication. The most significant issue identified in the survey was the need to increase the number of collaborations between different types of organisations, particularly collaborations between universities/institutes and industry/business, and between universities/institutes and government research organisations.

A Nanotechnology Stakeholder Day hosted by the Academy on 25 September 2009 enabled members of the different sectors of the nanotechnology research community to identify and discuss critical issues impeding the development of nanotechnology, and these included:

- collaborations between universities/institutes and industry/business in order to improve the opportunities for commercialisation of Australian nanotechnology;
- participation in international collaborations and linkages; and
- current nanotechnology infrastructure and equipment operational costs.

A series of potential solutions were identified by participants to address these important issues. Based upon the issues, the following prioritised recommendations have been developed.

## Recommendations

### Recommendation 1

The Australian Government should lead the production of a National Strategic Plan for Nanotechnology Research that is developed in consultation with the research community from universities, government research organisations, Australian industry/business, as well as other key stakeholders (eg state and territory governments).

### Recommendation 2

Long-term funding should be allocated by the Australian Government to an integrated nanotechnology network that simultaneously represents research and industry needs and is supported according to typical innovation development time frames, eg ten years. The network participants would be instrumental in the development and implementation of:

- The National Strategic Plan for Nanotechnology Research (Recommendation 1); and
- An appropriately funded online resource that includes:
    - mechanisms to promote discussion between industry and basic researchers;
    - lists of available nanotechnology infrastructure and equipment;
    - lists of current research and researchers; and
    - a database of intellectual property.

### Recommendation 3

Develop a single, centralised, national support mechanism for international collaborations and linkages at all scales which improves the timeliness (three month turnaround) and simplicity of the application process, administration processes and funding approval.

### Recommendation 4

In the short-term the Australian, state and territory governments should identify and allocate funding for the ongoing costs of existing nanotechnology infrastructure and equipment, and in the long-term incorporate operational costs, such as maintenance and the provision of technical staff, into infrastructure funding models.

### Recommendation 5

Funding agencies, while continuing to support basic research in nanotechnology, should orientate some support and funding towards encouraging 'market driven, problems-based' research.

### Recommendation 6

The Australian Government should establish, perhaps as part of the Commonwealth Commercialisation Institute, a nanotechnology entrepreneurial fellowship scheme that enables scientists to undertake placements with multiple members of industry to disseminate and foster particular sets of research for commercialisation.

### Recommendation 7

Federal, state and territory governments should maintain support and funding mechanisms for Australian-based nanotechnology collaborations, with dedicated schemes for postgraduate students and early-career researchers.

### Recommendation 8

Federal, state and territory governments should continue already successful efforts to integrate with research, industry and business in the development of science-based regulation and direct community engagement on nanotechnology issues.

# 1. Introduction

## 1.1 Innovation in the 21st century

In 1996 the Organisation for Economic Co-operation and Development produced a jobs strategy and said:

> Knowledge, especially technological knowledge, is the main source of economic growth and improvement in the quality of life. Nations which develop and manage effectively their knowledge assets perform better. [1]

Thirteen years later, Australia's reliance on knowledge and our capacity to innovate is still recognised by the Australian Government as critical to future prosperity:

> Australia's innovation system will need to work better if we want to maintain the way of life we value so much.[2]

The critical importance of knowledge and the translation of knowledge into technological outcomes for economic and social prosperity are firmly established. The emergence in the past few decades of enabling research fields such as ICT, biotechnology and nanotechnology has provided Australia with significant opportunities. Australia has the potential to apply these new technologies across a variety of industries and also to be at the forefront of the development of these research fields into new high-skill, high-wage employment opportunities. Nanotechnology is the most recent of these emerging research fields and its current status in Australia requires further investigation.

## 1.2 Nanotechnology

Nanotechnology was defined by the Australian Office of Nanotechnology in 2008 as:

> [A] … collective term for a range of technologies, techniques and processes that involve the manipulation of matter at the nanoscale – the size range from approximately 1 nanometre (nm = one millionth of a millimetre) to 100 nm ... The term nanotechnology describes the technologies used to create, manipulate and characterise matter and processes at the nanoscale.[3]

Undertaking research at the nanoscale became possible during the last 25 years due to advances across a number of research fields, providing the tools necessary to manipulate and measure at the nanoscale. By its very nature, nanotechnology crosses the traditional boundaries between research fields and is highly multidisciplinary, drawing together researchers from variety of physical and biological sciences. The implications of nanotechnology are also varied, with consequences across issues as disparate as health, the environment and industrial manufacturing.

The potential of nanotechnology has been recognised: with its capacity to revolutionise everything from computers to medicine, nanotechnology research has become the focus of funding bodies, regulators and governments in Australia during recent years. Although the focus of each group (researchers, industry and government) is different, the importance of nanotechnology for the future of Australia has led each to actively engage in a dialogue on the various issues surrounding the development of nanotechnology research into commercial products. A more cohesive approach to discourse on the translation of basic nanotechnology research into commercial outcomes has been facilitated in part by the existence of several government and non-government structural mechanisms.

## 1.3 Recent trends in Australian nanotechnology

During the past two decades nanotechnology has developed as a strong research field, with a continuously increasing proportion of global science publications and estimation in 2005 that by 2014 15% of global manufacturing will incorporate nanotechnology.[4] Australian nanotechnology has undergone a similar and significant growth since the early 1990s both in the scale of inputs and the number of outputs.

In 2004 the Academy undertook an Australia Research Council (ARC) funded benchmarking of Australian nanotechnology research to critique Australia's relative global position. Australian nanotechnology research was assessed as being of high quality across all areas of nanotechnology despite the small size of the research community. However, based upon the bibliometric data collected, concerns were raised with respect to whether Australia was developing its capabilities as rapidly as other nations. In support of these concerns was the finding that although significant investments had been made in nanotechnology research through the ARC and Commonwealth Scientific and Industrial Research Organisation (CSIRO), this was not being directed by a formal nanotechnology strategy or network. Australia was considered at risk of falling further behind the rest of the world due to an absence of networks and/or a strong nanotechnology strategy that focuses and directs nanotechnology research efforts, similar to those that exist in many other countries.

The Australian Government's Invest Australia published the *Nanotechnology Australian Capability Report*.[5] In 2007, nanotechnology research in Australia comprised 75 nanotechnology research organisations, including research institutions, universities, Cooperative Research Centres (CRCs), ARC Centres of Excellence (CoE), Australian Nuclear Science and Technology Organisation (ANSTO) and the CSIRO, and approximately 80 nanotechnology companies. A significant quantity of nanotechnology research was recognised to occur in research organisations, a feature of the Australian innovation sector.[6] The *Nanotechnology Australian Capability Report* incorporated a review of Australia's capacity across the various nanotechnology research areas, including descriptions of all of Australia's major research facilities. A matrix of Australian nanotechnology clearly illustrated that the nanotechnology research organisations and nanotechnology companies have capacities in a variety of different fields, such as materials, nano-biotech and medical devices, energy and environment, electronics and photonics, quantum technology, instrumentation and software. Australia also had a variety of facilities, networks and associations.

During 2007 the Australian Government announced the development and implementation of a National Nanotechnology Strategy (NNS). The strategy's aim was to help Australia capture the benefits of nanotechnology, whilst also addressing the risks, and complementing existing initiatives, research and policies. Specifically, the strategy aimed to:

- address the health safety and environmental (HSE) impacts of nanotechnology on regulations and standards;
- undertake a public awareness and engagement program to provide balanced advice on nanotechnology;
- establish a nanoparticle metrology capability at the National Measurement Institute; and
- facilitate a whole of government approach to nanotechnology through establishing the Australian Office of Nanotechnology.[7]

As part of its reporting on the implementation of the NNS, the Australian Office of Nanotechnology published its' 2007–08 Annual Report. The report did not include updated figures on the size of the nanotechnology community, using those previously provided in the *Nanotechnology Australian Capability Report*. However, the report did outline that 31 of Australia's nanotechnology groups were from only 14 of Australia's 41 universities.[8] This indicates that nanotechnology research is concentrated in a small, highly specific set of Australia's universities and research institutions. The Australian Office of Nanotechnology also went on to describe the majority of the estimated 80 nanotechnology companies as small- to medium-enterprises (SMEs),[9] another prominent feature of the Australian innovation sector.[10]

These two recent reports highlighted the existence of several different networks for nanotechnology in Australia that vary in their goals and aims. The Australian Research Council Nanotechnology Network (ARCNN) began in 2005 and is supported by the ARC. The ARCNN aims to draw together researchers from across the various sub-disciplines within nanoscience and nanotechnology. Through the provision of conferences, workshops, summer schools, student and early-career research training and various other projects, the network enhances researcher interactions at a local and international level.

The Australian Nano Business Forum (ANBF) is a national peak body that represents companies and industries engaging in nanotechnology. The forum's goal was to provide both a voice for their members and also to facilitate linkages with key stakeholders such as government, funding bodies, regulatory and research entities.

The Australian Nanotechnology Alliance (ANA) is an alliance composed of members from a variety of industries. The ANA aims to encourage collaborations between three key stakeholders (researchers, developers and manufacturers) and increase awareness of the potentials of nanotechnology.

The final two networking entities, The A to Z of Nanotechnology (AZoNano) and Nanotechnology Victoria (NanoVic), differ from the previous three networks in that they do not have a national focus. AZoNano is an online resource that aims to inform engineers, designers, academics and scientists around the world through the provision of technical data and expert listings. NanoVic was originally a consortium of several Victorian universities and the CSIRO but subsequently developed interactions with researchers and corporations around Australia. The focus of NanoVic was identification of industrial applications of nanotechnology. NanoVic, although originally a state-based organisation, participated in national research activities, the regulation of development and progression of the NNS.

## 1.4 2009, a year of change

During 2009 there have been numerous changes in the nanotechnology community, particularly with regard to the NNS and the various networks. These changes are still ongoing, and the complete impact remains unclear, but it seems that there will be an impact.

The Australian Government announced in the 2008 budget that the NNS would cease two years early on 30 June 2009. In the 2009 budget, as part of its innovation agenda, the government announced the establishment of the National Enabling Technologies Strategy (NETS). Consultations have been conducted on the detail of the strategy with the Australian Office of Nanotechnology transitioning to manage implementation of the NETS. By building on the previous NNS and the National Biotechnology Strategy (NBS), NETS is to provide a framework for the responsible development of enabling technologies such as nanotechnology and biotechnology and other technologies as they emerge in Australia.[11] Again, the strategy will focus on policy development, regulation and public engagement, rather than on current nanotechnology research.

NanoVic was to end mid-2009 and the company NanoVentures Australia Ltd was developed to replace it. However, NanoVentures Australia Ltd did not continue (due to a lack of funding) and, in the absence of an alternative strategy, the entire enterprise was closed down at the end of August 2009. Several of the staff moved into consulting (eg Quintain Consulting) but other staff are no longer working in the nanotechnology field.

Due to a similar loss of funding the ANBF, located in Victoria and supported by the state government, had by September ceased to operate. Again some previous members of the board and staff are attempting to continue to support business engagement with nanotechnology research, but this shift is ongoing and it is unclear if any suitable replacement organisations and support mechanisms will be developed.

As with all of the ARC networks, the ARCNN will not be funded beyond 2009 due to their described budgetary constraints. Efforts are being made to identify an alternative support mechanism for 2010 onwards, but no arrangements are as yet in place.

Currently, the ARCNN represents approximately 1,000 active researchers, composed of approximately 50% students and 50% professional researchers from universities, institutes and government research organisations. Government research organisation staff engaged in nanotechnology research may not have joined the ARCNN, due to its perceived university focus. Previous government reports identified approximately 80 nanotechnology companies, but nanotechnology industry members now estimate that this has dropped to approximately 55 to 60 companies, which are mostly SMEs with an estimated 5 to 20 staff per company.[12] This significant decrease in the number of companies was described as being a result of the loss of investment due to the global financial crisis and the termination of the Commercial Ready Australian Government program.

Based upon ARCNN membership figures and the suggested reduction in Australian nanotechnology companies, it is estimated that there are 2,000 people in Australia engaged in nanotechnology research. Researchers from universities and institutes form approximately 50% of this population, but this figure would likely rise to 60 to 70% if researchers from government research organisations (who can be, and are, members of the ARCNN) were also included.

The absence of an ongoing funding source to support Australian nanotechnology networks could severely reduce linkages between the members of the community and the formation of linkages with industry and business communities, and international nanotechnology researchers. This lack of connectivity would likely impede, and could potentially halt, the advance of nanotechnology research in Australia.

## 1.5 Research into Australia's nanotechnology research community

Since June 2009 the Australian Academy of Science has undertaken qualitative and quantitative research activities to characterise nanotechnology research in Australia. A bibliometric analysis of Australian publications in the field of nanotechnology was conducted using Web of Science publications to the end of 2008. This data was then compared to the collected bibliometric data and consequent findings of the Academy's 2004 report *Nanotechnology Benchmarking Project*.[13] The findings of the current bibliometric analysis and the previously identified publication trends are described in Chapter 2.

During a seven week period in mid-2009 the Academy undertook the Survey of Australian Nanotechnology Research Trends and Collaboration Networks. This survey was distributed to researchers in universities and institutes, government research organisations and industry/business through three nanotechnology networks. The collated data and findings of the survey are presented in Chapter 3.

On 25 September 2009 a one day stakeholder event was hosted by the Academy at the Shine Dome in Canberra. The Nanotechnology Stakeholder Day was attended by approximately 40 invited participants from universities, institutes, government research organisations, and the industry and business sectors. Participants were presented with information on nanotechnology research and commercialisation in Singapore, and the preliminary data from the Academy's survey of nanotechnology research in Australia. They later participated in a series of discussions on issues relevant to nanotechnology research in Australia. The outcomes of the Stakeholder Day are presented in Chapter 4.

Chapter 5 reports the current nanotechnology research trends in Australia from the bibliometrics data and the results of the 2009 survey. Collaborations and linkages were also a focus of both the bibliometric analyses and the collated survey data, with several important trends being identified and discussed. A series of nanotechnology community derived recommendations to improve and develop Australian nanotechnology research and research outcomes are also described in Chapter 5, based on the issues identified in the survey and the discussions held during the Stakeholder Day.

An ARC Learned Academies Special Project grant supported the research into Australian nanotechnology research trends and collaborations. It is the first comprehensive analysis of these topics with regard to the nanotechnology field and significantly increases knowledge of this crucial emerging technology.

# 2. Bibliometric benchmarking of Australian nanotechnology

## 2.1 Bibliometric benchmarking

Since 2001 the Australian Academy of Science has conducted several benchmarking exercises based upon a methodology derived from the US Committee on Science, Engineering and Public Policy (COSEPUP, 2001). One such bibliometric benchmarking was undertaken with ARC funding during 2003–04 on nanotechnology in Australia.[14] The results of this analysis were published in 2004 and indicated that nanotechnology was a growing field for which Australia had a slightly lower percentage of world publications than for science as a whole. Nanotechnology publications as a percentage of world science and Australian science had been steadily increasing since the 1990s (approximately a 6 to 7% increase per year), indicating that nanotechnology was becoming a significant field of research both nationally and internationally. In 2004, bibliometric data indicated that nanotechnology was not as high a proportion of science publications for Australia as it was for many other countries, particularly several Asian countries where nanotechnology publications represented a significantly higher percentage of science publications than the global average.

The number of Australian nanotechnology publications with international co-authors had also been steadily increasing since the early 1990s. Of particular interest was the finding that Australian nanotechnology publications had a higher rate of international collaborations than for Australian science publications in general. The frequency of collaboration with particular regions was highly variable from year to year, but the most significant trend was the large increase in the proportion of joint nanotechnology publications with Asian nations, which was far greater than for joint publications with Asian nations across all science. Although the 2004 report considered a wider range of issues and sources of data, the bibliometric analysis undertaken was central to the report's conclusion that:

> Australian nanotechnology researchers are producing high-quality work across all areas of nanotechnology, but there is evidence that we are not advancing our capabilities as quickly as the rest of the world.[15]

To examine developments and trends since 2004, a bibliometric analysis of nanotechnology publications up to the end of 2008 was undertaken using a methodology based upon that used in 2003–04, but adjusted for application to 2009 databases.

## 2.2 Bibliometric analysis methodology for 2009 study

A database of Australian nanotechnology publications was compiled from the Thomson Reuters ISI Web of Science online publication database using a series of Boolean string searches. The Boolean strings (detailed in Appendix 1) were derived from the strings used in the 2004 bibliometric analysis but were updated to accommodate modern publication numbers and changes to ISI Web of Science. Each Boolean string was searched with and without AUSTRALIA included as a co-search term in the Address field for collection of all of the required data.

The collected data was stored as EndNote files which were subsequently sorted to provide the numbers necessary for the development of each of the following graphs.

As described in the Academy's 2004 publication on nanotechnology benchmarking, there are limitations to this method of collecting and analysing nanotechnology publications. The most significant is under-representation of particular fields or topics, and the incorrect inclusion of publications due to the Boolean strings utilised. However, the use of new and updated strings in this study that still resulted in similar publication trends as those observed in the 2004 study would tend to indicate that the findings are robust and representative of nanotechnology publications and science publications more generally.

## 2.3 Results from bibliometric analysis

Australia's number of nanotechnology publications has been steadily increasing since the early 1990s (Figure 2.1). This trend is similar to that observed during the 2004 study, including a similar pattern of rapid rises, followed by short plateaus in 1997–98 and 2001–02. The similarity between the graph in Figure 2.1 and Figure 1 from the 2004 report indicates that the publication data collected in this study (using new Boolean strings) is robust and that any consequent findings are likely to be comparable to those from the previous study.

An examination of Australia's 'all science' and nanotechnology publications relative to global publication trends highlights the growth of nanotechnology since the mid-1990s (Figure 2.2). Nanotechnology publications as a percentage of world science or Australian science publications have nearly doubled in the last ten years. Over the same time, Australia's share of both world science and world nanotechnology publications has remained relatively constant. Australia's share of world nanotechnology publications still remains slightly less than the Australia's percentage of world science publications.

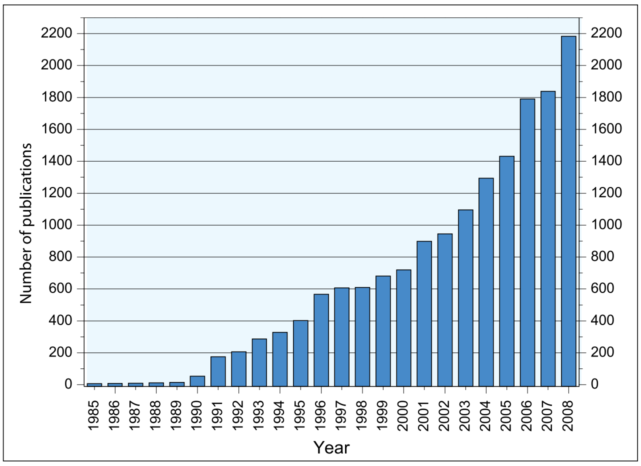



Figure 2.1 Number of nanotechnology publications between 1985 and 2008

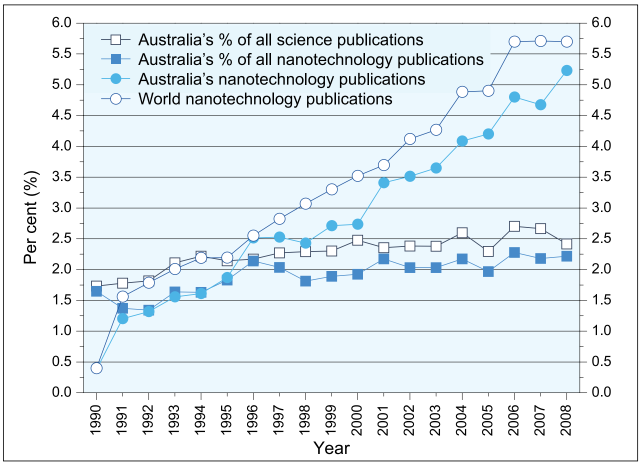



Figure 2.2. Australian science and nanotechnology publication trends, 1990 to 2008

Although Australia is slightly behind global trends, it is clear that nanotechnology research has become a significant research discipline both nationally and internationally.

Although Australia still has less than global averages for nanotechnology publications as a percentage of total science publications (Figure 2.2 and Figure 2.3), the situation has improved significantly since 2004. Australia is now publishing at approximately 90% the world average, whereas Australia was only producing at a rate 60 to 70% of the world average in 2004. This is due to an increase of 155 to 160% in Australia's nanotechnology publications as a percentage of total science publications compared to only a 70 to 100% increase in the world averages over the same period. Several Asian countries are still publishing well above the world average, but these nations have now been joined by the US and several European nations. Nanotechnology research has become a strong research field in many different countries around the world.

A closer examination of several countries' publication trends for 'all science' (Figure 2.4) revealed that in recent years the proportion of 'all science' publications for major research countries like England and Japan has declined, whilst China's proportion of 'all science' publications has risen significantly. Nanotechnology publications as a proportion of 'all science' publications data (Figure 2.5) indicates that although there has been a steady increase for all represented countries, some countries (such as China) have undergone an even more rapid increase in publication number.

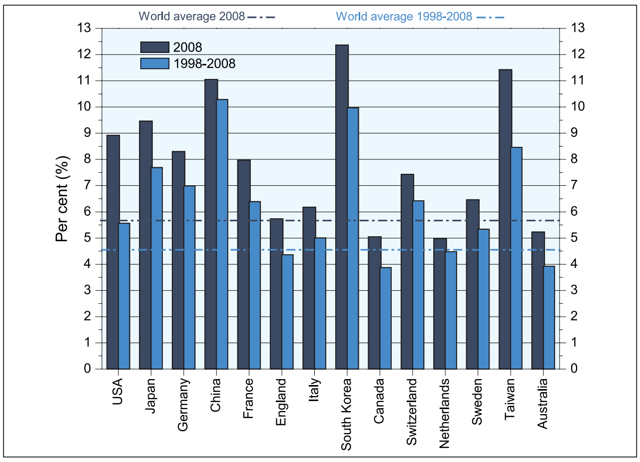



Figure 2.3. Nanotechnology publications as a percentage of science publications for selected countries

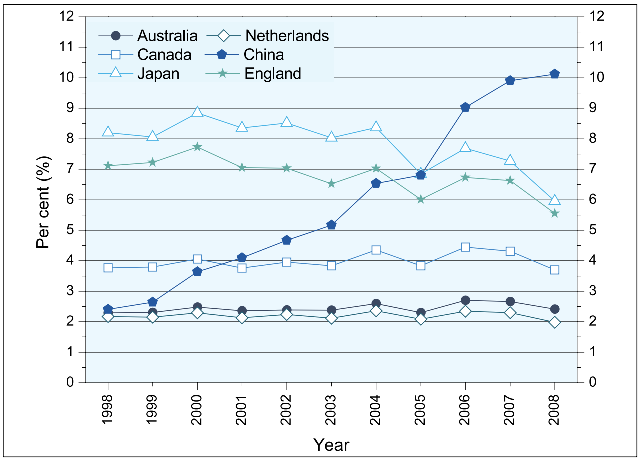



Figure 2.4. All science publications for selected countries, 1998 to 2008

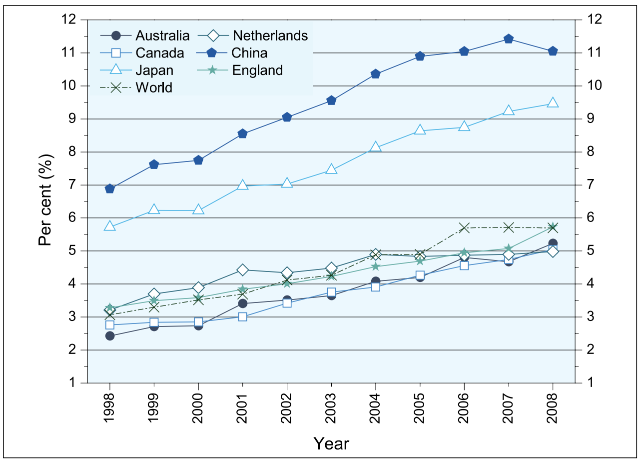



Figure 2.5. Nanotechnology publications as a percentage of all science publications for selected countries, 1998 to 2008

An analysis of who Australian researchers are publishing with (Figure 2.6) indicates that there has been a significant rise in joint publications with international researchers for both nanotechnology and 'all science'. This rise in joint publications with international researchers has been so strong that by 2002 joint publications with international collaborators had surpassed the percentage of publications involving only Australian authors.

The rapid decline in Australian-only authored papers has been so strong that by 2008 for both 'all science' and nanotechnology they represented approximately 35% of publications. Australian science research, including nanotechnology, is very strongly integrated with the international research community.

A closer examination of Australia's top five collaborators by publication (Figure 2.7 and Table 2.1) shows different trends for 'all science' compared to nanotechnology. (Note: in some years France replaces Japan, but for simplicity only the top five countries for the decade 1999 to 2008 were graphed). Except for China, since the early 1990s 'all science' publications for each of the represented countries have remained a relatively constant proportion of all publications with international co-authors. Since 1998 Australia's rate of collaboration with China across 'all science' has steadily increased, such that it is now Australia's third highest collaboration partner by publication. For nanotechnology collaborations, the percentage of joint authored publications for each of the countries represented has been far more variable over the past 18 years, with greater variability year to year than observed for 'all science' (most likely due to the smaller sample size). Of note was the significant decline since the early 1990s in the proportion of joint authored publications involving the US and England;

Table 2.1. Australian nanotechnology publications with collaborations for different countries*

| Country | No. of collaborations |
|---|---|
| US | 1554 |
| Peoples R China | 818 |
| England | 749 |
| Germany | 588 |
| Japan | 409 |
| France | 307 |
| Singapore | 236 |
| Canada | 230 |
| New Zealand | 190 |
| Italy | 174 |
| Sweden | 171 |
| South Korea | 170 |
| Switzerland | 156 |
| Netherlands | 134 |
| Spain | 112 |
| India | 106 |
| Scotland | 98 |
| Russia | 88 |
| Poland | 83 |
| Denmark | 76 |
| Israel | 70 |
| Belgium | 64 |
| Brazil | 59 |
| Ireland | 59 |

* top 24 countries for the 10-year period 1999-2008

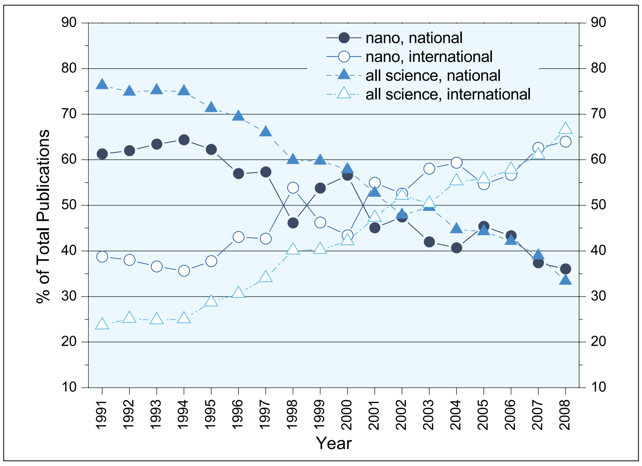



Figure 2.6. Percentage of Australian 'all science' or Australian nanotechnology publications involving national or international collaborations

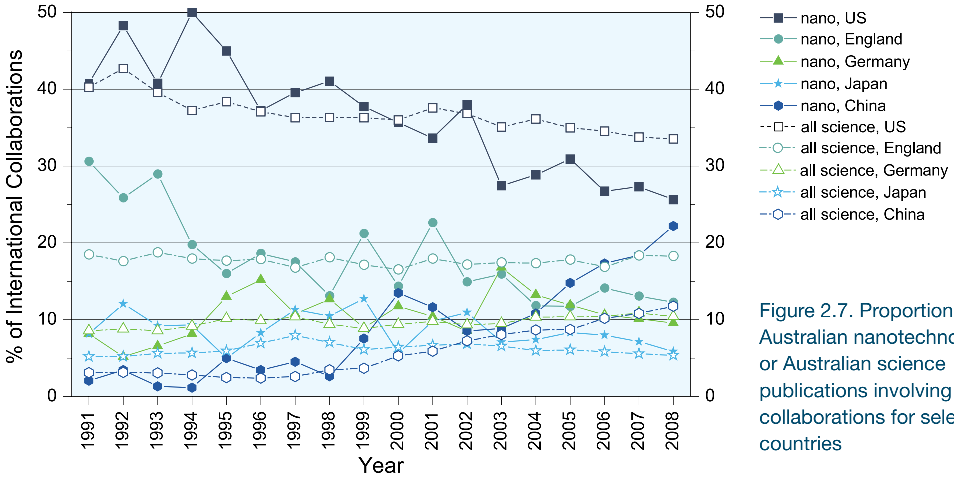



Figure 2.7. Proportion of Australian nanotechnology or Australian science publications involving collaborations for selected countries

approximately 45% and 60% decreases, respectively. Again, collaborations with China were on the rise, such that by 2008 China was Australia's second largest nanotechnology collaboration partner measured by proportion of joint publications with international co-authors.

## 2.4 Bibliometric analysis conclusions

Australia's nanotechnology publication rate per year has continued to grow since it was last measured by the Academy in 2004, with the number of publications per year having approximately doubled in that time. As nanotechnology publications have formed a greater percentage of Australia's total science publications, Australia has come closer to achieving world average publication rates for nanotechnology. This is in contrast to 2004 where Australia was significantly below the world average. Scientific research, and specifically nanotechnology, more than ever before involves international collaborations. For nanotechnology there has been a very strong increase in the collaborations involving China, with a corresponding decline in the proportion of joint publications with previously dominant collaboration partners such as the US and UK. This bibliometric analysis indicates that Australia has significantly improved its nanotechnology publication output with respect to global averages but that Australian publication rates still remain lower than global averages. Whilst publication rates are not necessarily indicative of quality or worth, the observation highlights room for improvement relative to our global competitors in the rapidly expanding and advancing research field of nanotechnology.

# 3. Survey of Australian nanotechnology research trends and collaboration networks

## 3.1 The survey

A survey was developed by the Academy's 2009 nanotechnology research project advisory group and secretariat staff to examine the issues surrounding Australian nanotechnology research and collaborations. A copy of the survey is provided in Appendix 2. A link to the online survey of 19 questions was distributed via nanotechnology networks (ARCNN, ANBF and the ANA). Invitees to the Nanotechnology Stakeholder Day were also provided with the link to the survey.

Responses were collected over seven weeks using eSurveysPro (online survey software). Reminders were sent to members of the ARCNN, ANBF and ANA in which network members were also encouraged to distribute it to others who might be interested. As part of the final email reminder to ARCNN members a PDF copy of the survey was provided as an email attachment. As an incentive to complete the survey, an IPod Nano (valued at approximately $300) was provided as a prize to a randomly-selected person who had completed the survey.

At the end of the seven weeks the responses were exported from the eSurveysPro site and sorted by participant name in Microsoft Excel. Any obvious duplicates or surveys where no name or data were provided were deleted. Analysis was carried out on the remaining 316 responses.

## 3.2 Data analysis

Since the design of the survey enabled participants to provide more than one answer to each question, responses do not necessarily total 100%. Less than 40% of respondents answered all questions, so each question has been analysed based upon the number of respondents to that particular question. Categories were self-selected or determined during analysis of survey responses.

## 3.3 Biographical data

The distribution of survey participants by their position or role in an organisation (Figure 3.1) was commensurate with differences in the number of researchers of different positions in the research community. The greatest number of respondents classified themselves as staff, which would include

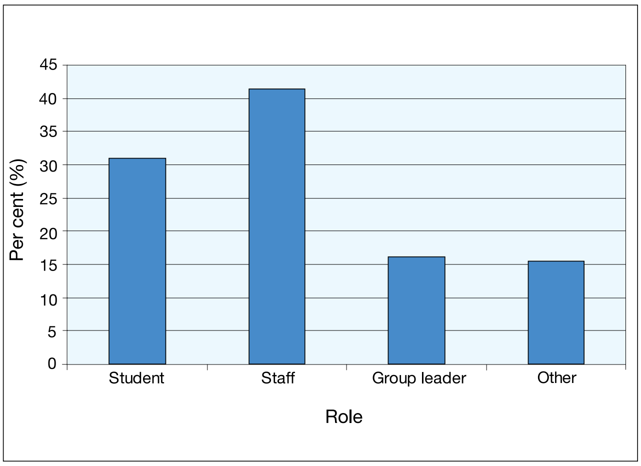



Figure 3.1. Respondent's role in organisation

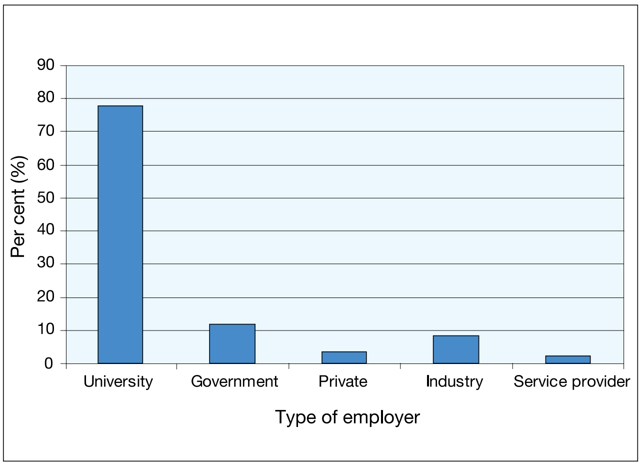



Figure 3.2. Types of employers

technicians, research assistants and postdoctoral fellows not in a group leader position. Students had the second highest response rate, followed by group leaders and those who classified themselves as 'other' (such as a company director).

Responses by employer type showed a significant weighting to university (Figure 3.2), with nearly 80% of respondents classifying their employer as a university. Government was second at slightly more than 10%. All other employer types (private, industry and service provider) represented less than 10% each of the total responses.

## 3.4 Nanotechnology research trends

Respondents were able to select one or more of eight possible fields to describe their current nanotechnology research. The eight fields used were based on those used in the third edition of the *Nanotechnology Capability Report* and were:

- materials
- nano-biotech or medical devices
- energy and environment
- electronics and photonics
- quantum technology
- nanocharacterisation
- simulations and modelling
- other (please specify).

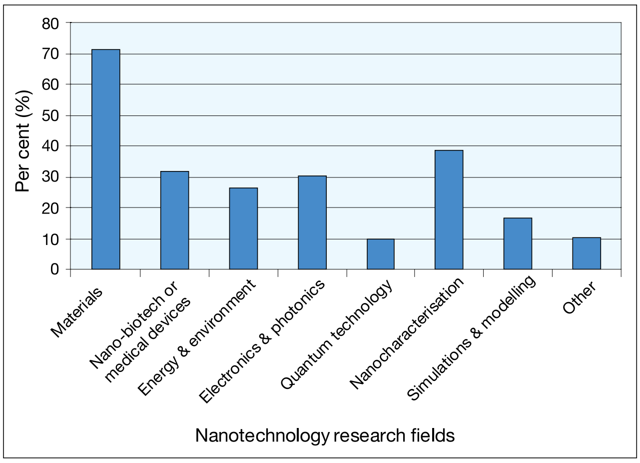



Figure 3.3. Proportion of researchers in different fields of nanotechnology research

By far the greatest response was for the category of materials research (Figure 3.3), with approximately 70% of respondents selecting this category to describe their research. Between 25 and 40% of survey respondents selected nanocharacterisation, nano-biotech or medical devices, electronics and photonics, and/or energy and environment to describe their research. Responses were received for all categories, suggesting that Australian nanotechnology research is distributed across the full range of potential fields.

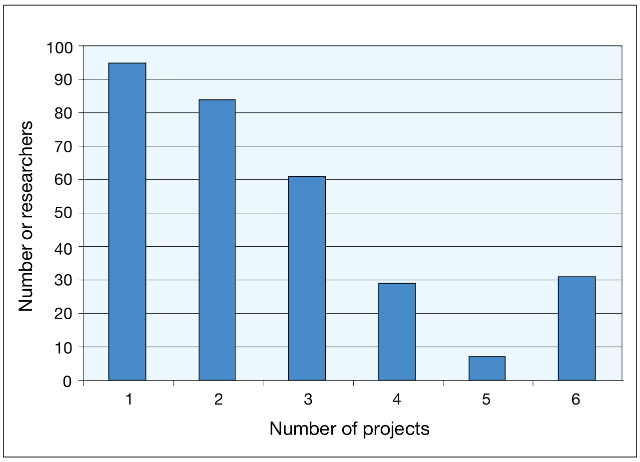



Figure 3.4. Number of research projects in which researchers are involved

Survey respondents were then asked to identify the number of research projects they are currently undertaking and the stage of each project's development (between basic research and commercial production). Over 30% of respondents had only one project (Figure 3.4), which was anticipated given the number of survey respondents who were students or in a staff position. The number of projects steadily decreases until the last option (six projects), which saw an unexpected rise above the number of respondents who had four or five projects.

This is most likely because respondents were unable to describe more than six projects due to a limitation in the survey design making it impossible to distinguish between researchers undertaking six projects and those who have more. This limitation of the survey design would need to be addressed in any future collections of data on nanotechnology research.

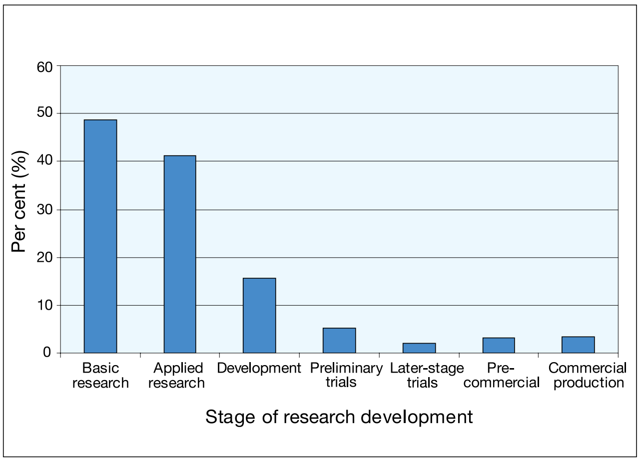



Figure 3.5. Percentage of projects at each stage of research development

The vast majority of projects were defined as being in the earliest stages of development – basic and/or applied research (Figure 3.5). This is not surprising given that the majority of respondents to the survey were from universities, and also given that most research is not ever developed beyond these early stages. Respondents identified projects at all stages of development that were offered as options in the survey.

When examining the stages of project development the trend was increasing stage of development the higher the project number (Figure 3.6). Project 1 has the highest percentage of research described as being basic, whereas Project 6 has the highest percentage of research described as being at the stage of commercial production. Those who described six projects held higher positions, such as group leader or director, and therefore had had the opportunity to develop research all the way through to commercial production. When the stage of research development was examined by position (standardised for the number of responses by individuals of that position) (Figure 3.7) it became apparent that only those who had described their position as 'other' had a significantly different profile, with far more projects at the pre-commercial and commercial production stages of development, compared to student, staff or group leaders. Unsurprisingly, students did not have any research at the stage of commercial production but otherwise the research development profiles for students, staff and group leaders were relatively similar. This was unexpected given that group leaders would be anticipated to have significantly more research at later stages of development.

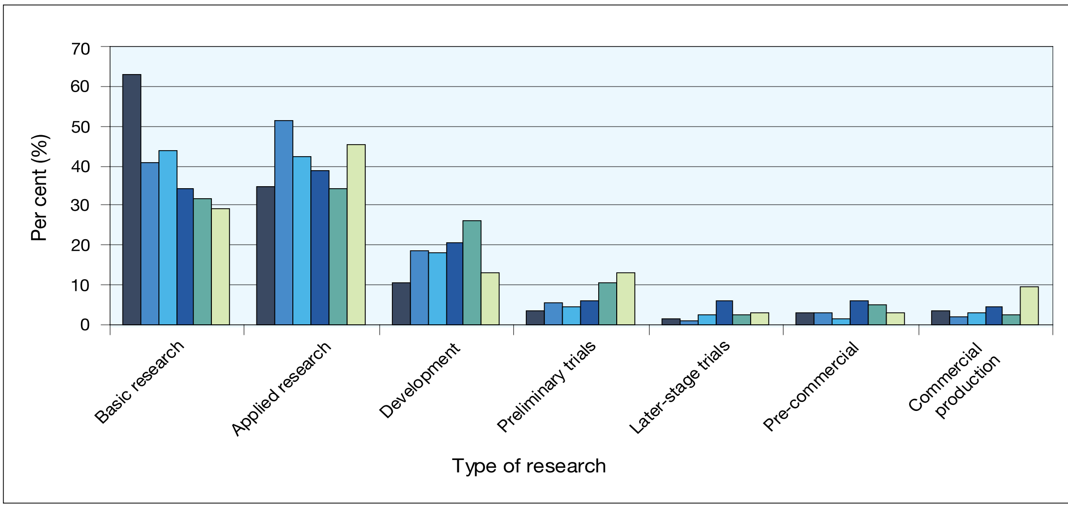



Figure 3.6. Proportion of each project number at different stages of research development

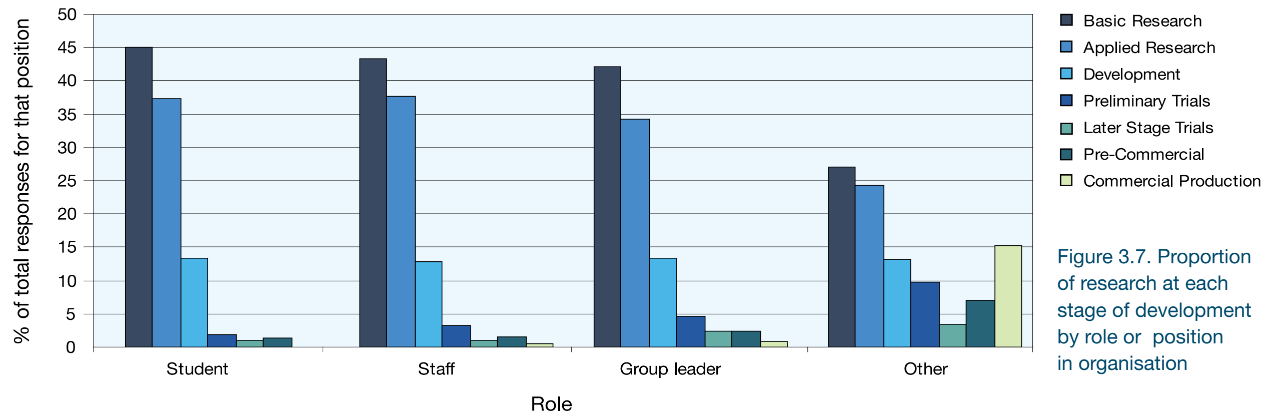



Figure 3.7. Proportion of research at each stage of development by role or position in organisation

## 3.5 Research collaborations

The next section of the survey focused on the participants' research collaborations. The first question was to determine if participants had any research collaborations. A surprising 23% of respondents indicated that they did not have any research collaborations (Figure 3.8).

To identify whether this related to their position or role in the organisation, all responses to the question and only those that responded 'no' were graphed by position (Figure 3.9). It can be clearly seen that 'no' responses were positively weighted towards students and to a lesser degree those in the 'other' category (including managers and company directors). This is perhaps to be expected given that students may not have yet had the opportunity to develop their own research collaborations. Group leaders were under-represented amongst the 'no' responses, but this too was unsurprising given that very few groups could function in modern research without access to collaborations. Overall the number of respondents that replied 'no' is of concern, but this is tempered by the finding that students were a significant proportion of these responses.

Survey respondents were asked to describe up to 10 collaborations and provide information about the type(s) of exchanges involved. Nearly 700 collaborations were described by survey participants and these are mapped in Figure 3.10.

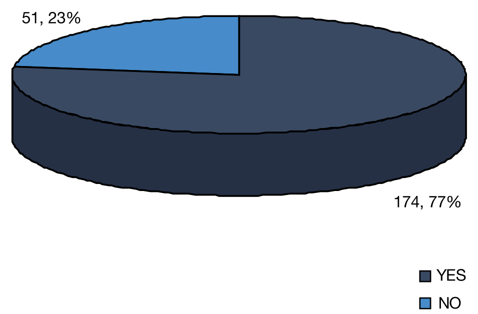



Figure 3.8. Number and percentage of survey respondents who have collaborations

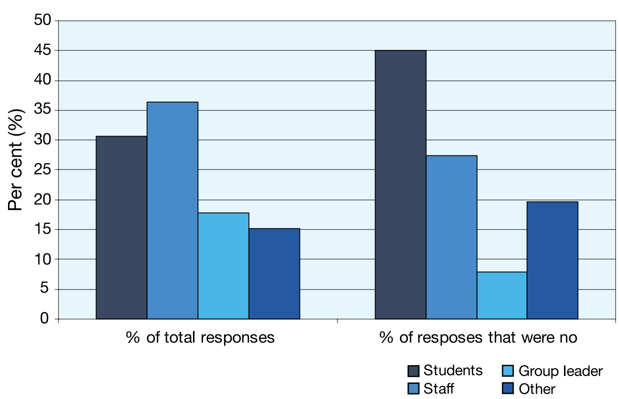
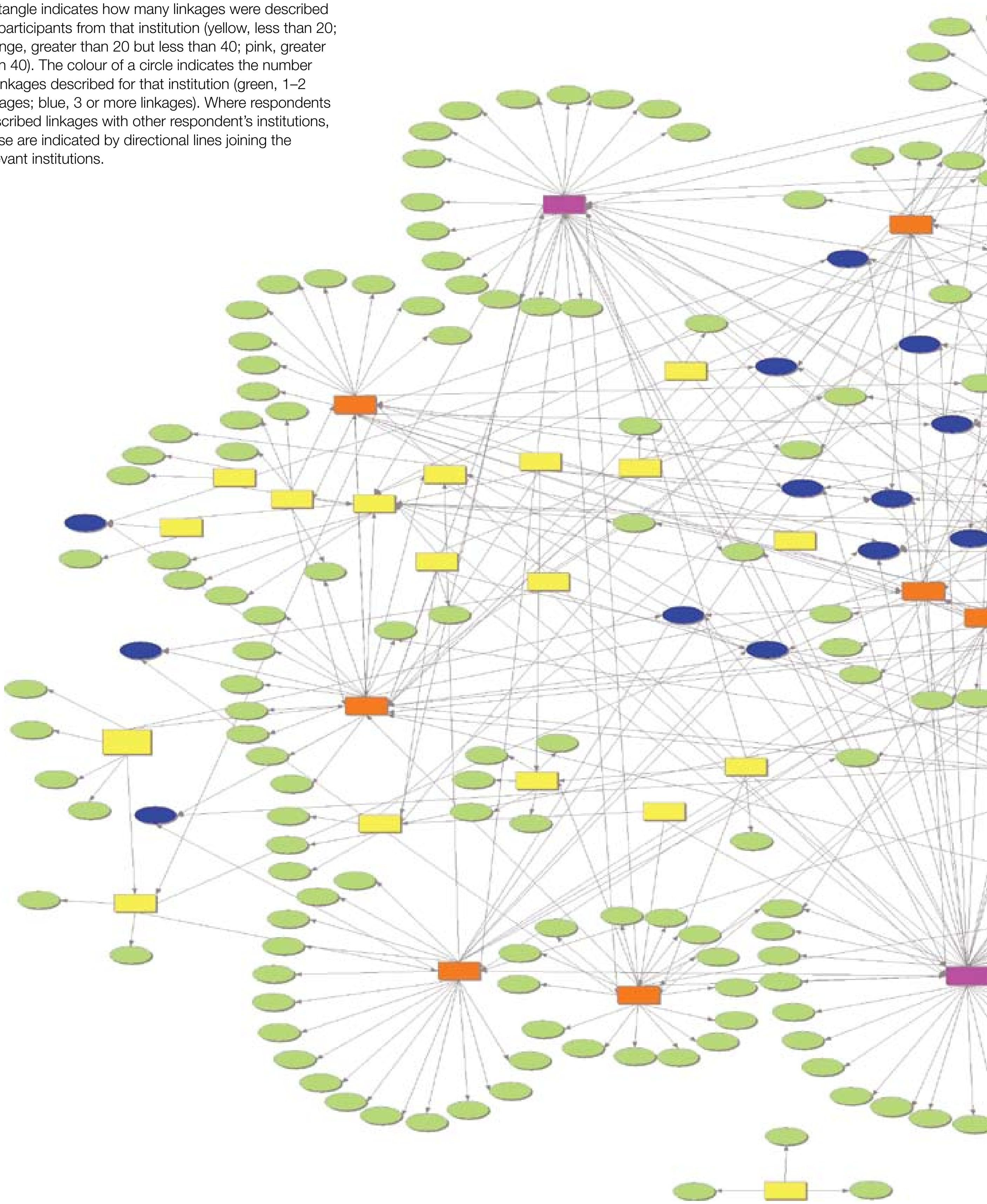
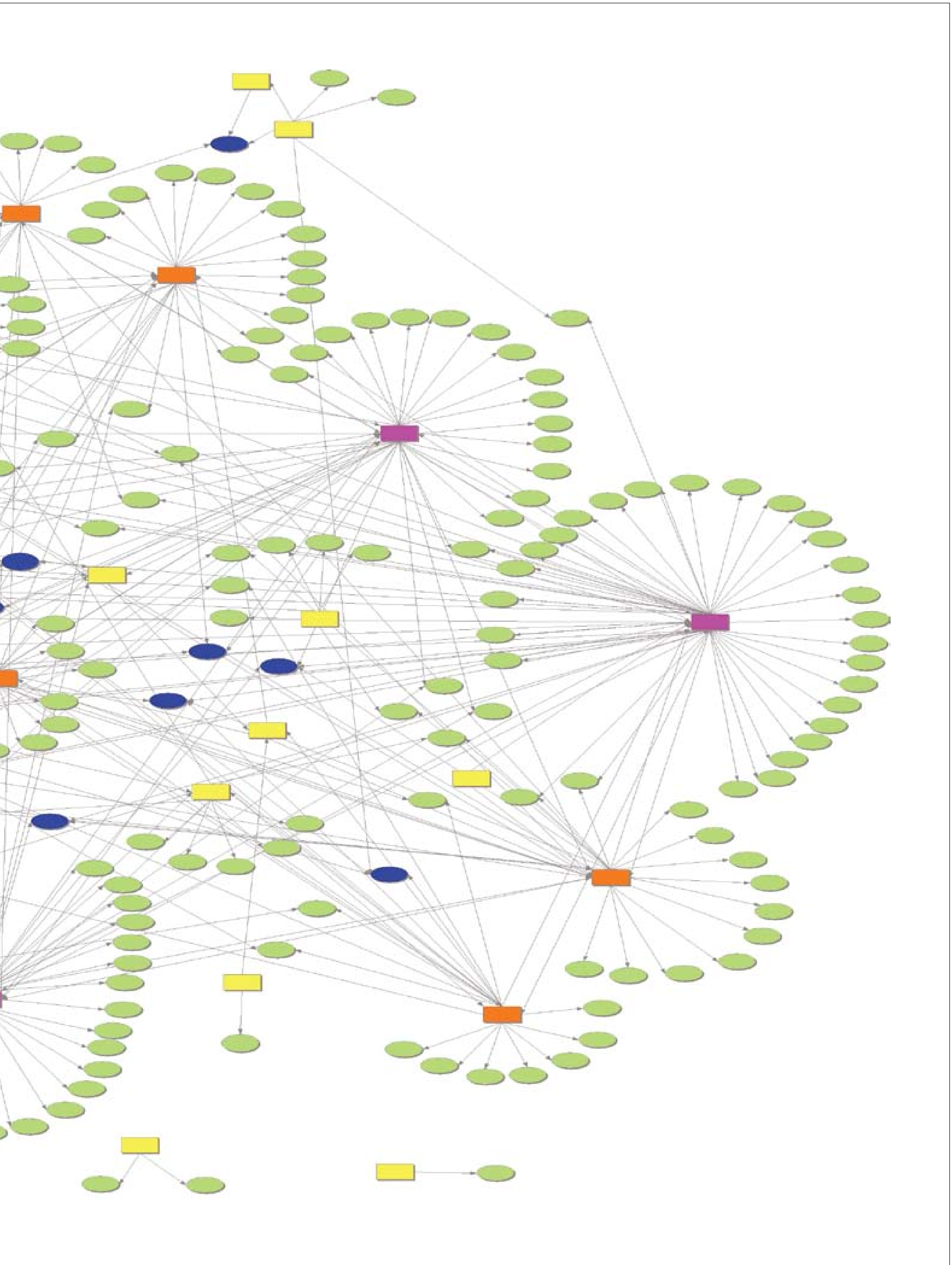



Figure 3.9. Percentage of survey respondents by position who have collaborations, and those who do not

Figure 3.10. Map of institutions with collaborating researchers (individuals not identified)

Rectangles indicate the institutions of researchers who responded to the survey; circles represent institutions with which respondents collaborate. The colour of a rectangle indicates how many linkages were described by participants from that institution (yellow, less than 20; orange, greater than 20 but less than 40; pink, greater than 40). The colour of a circle indicates the number of linkages described for that institution (green, 1–2 linkages; blue, 3 or more linkages). Where respondents described linkages with other respondent's institutions, these are indicated by directional lines joining the relevant institutions.





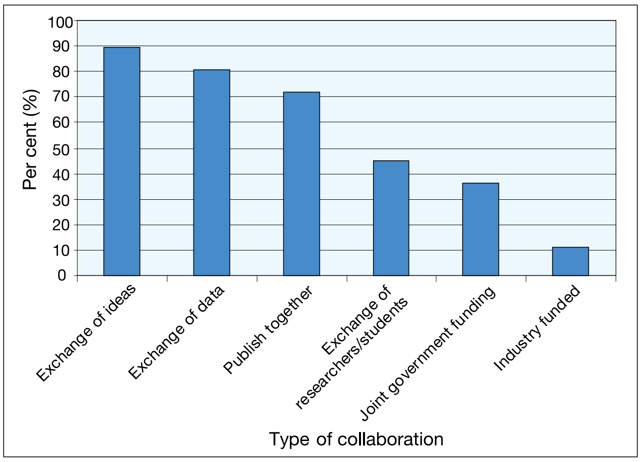



Figure 3.11. Types of collaborations

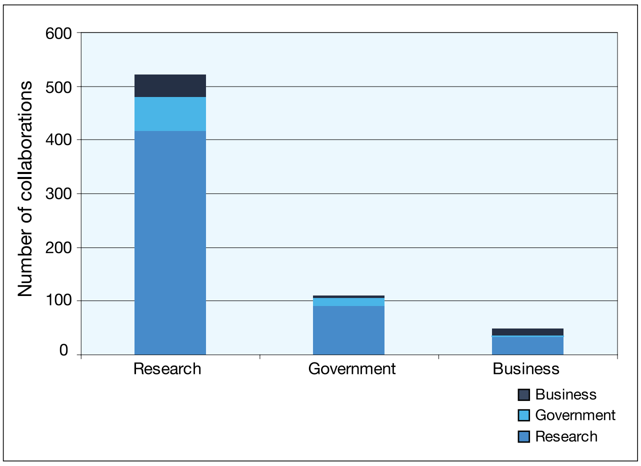



Figure 3.12. Number and type of collaborations for each type of organisation

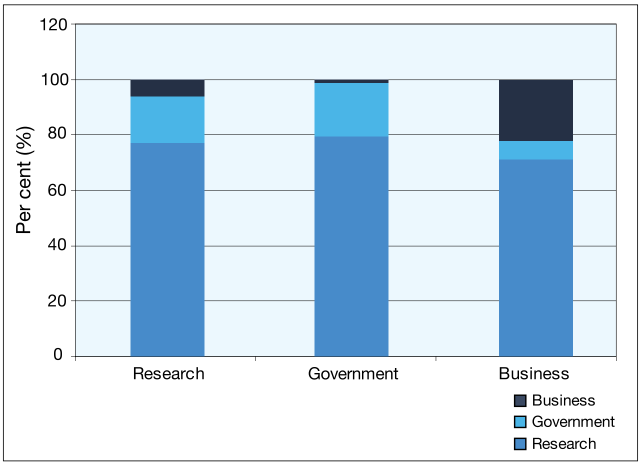



Figure 3.13. Relative percentages of collaborations for each type of organisation

Of particular note is the large number of collaborations that do not involve more than the respondent describing the collaboration and their collaborating organisation; that is, there are not multiple people connecting to the same institution from several different Australian institutions. This indicates that many of the collaborations are between individuals, based on personal relationships. Respondents indicated that their exchanges mostly involved the exchange of ideas, data and/or joint publication (Figure 3.11). Responses were seen for all types of exchanges suggesting that collaborations can and do involve many different types of interactions and exchanges.

Each of the collaborations was examined to identify what types of institutions were involved. Respondents were classified (not self-selected but based on respondents' institution) as being from research (universities or research institutes), government or industry/business. Each of the collaborators were similarly classified. As can be seen in Figure 3.12, by far the majority of collaborations described were by respondents from 'research'. Each category was standardised by the number of respondents for that category to identify collaboration trends (Figure 3.13). The vast majority of collaborations/linkages described by those from 'research', 'government' and 'industry/business' were with 'research'. This characteristic is due both to the number of survey respondents from universities and also the significant proportion that university and research institute researchers represent of the entire nanotechnology community. Respondents from 'industry/business' had a higher frequency of forming collaboration with 'industry/business' and 'government' had a higher frequency of forming collaborations with 'government'; like collaborated with like. Although the small sample sizes of collaborations described for these two categories may have influenced the robustness of these figures it warrants further consideration.

The research collaborations were also examined by country (Figure 3.14), with slightly more international than Australian collaborations being described.

Australian collaborations had similar profiles for the types of exchanges involved (Figure 3.15) as compared to the data presented for all collaborations (Figure 3.11). Examining the types of exchanges involved for each of the countries (Figure 3.16a and b) shows several important traits. There are a limited number of countries for which Australia had significant number of different collaborations, the top five being US, UK, China, Germany, France and Japan (equal 5th). All countries seem to show a relatively similar collaboration profile to those for all collaborations, in that the collaborations mostly involved the exchange of ideas, data and joint publication.

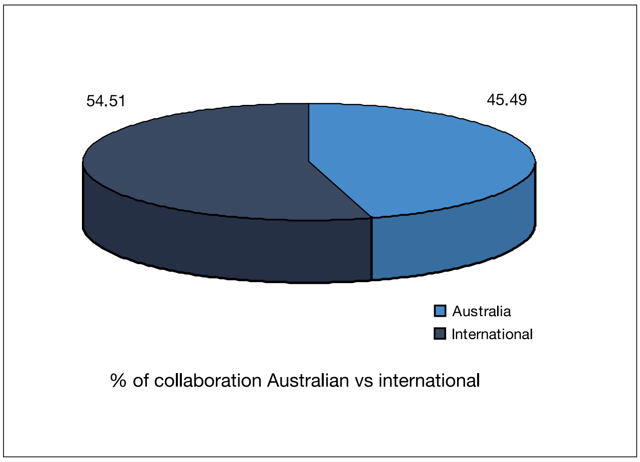



Figure 3.14. Australian versus international collaborations

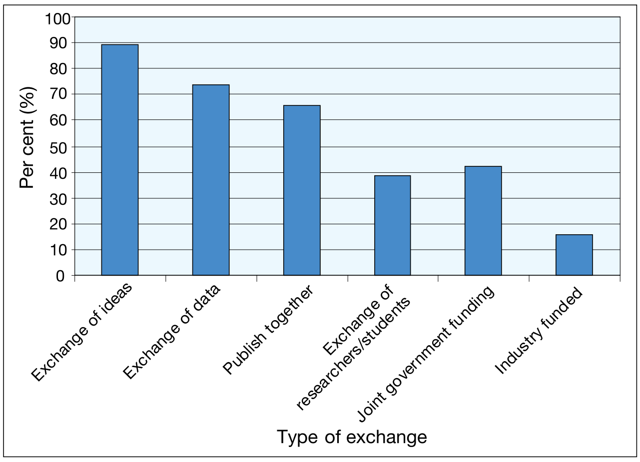



Figure 3.15. Types of Australian collaborations

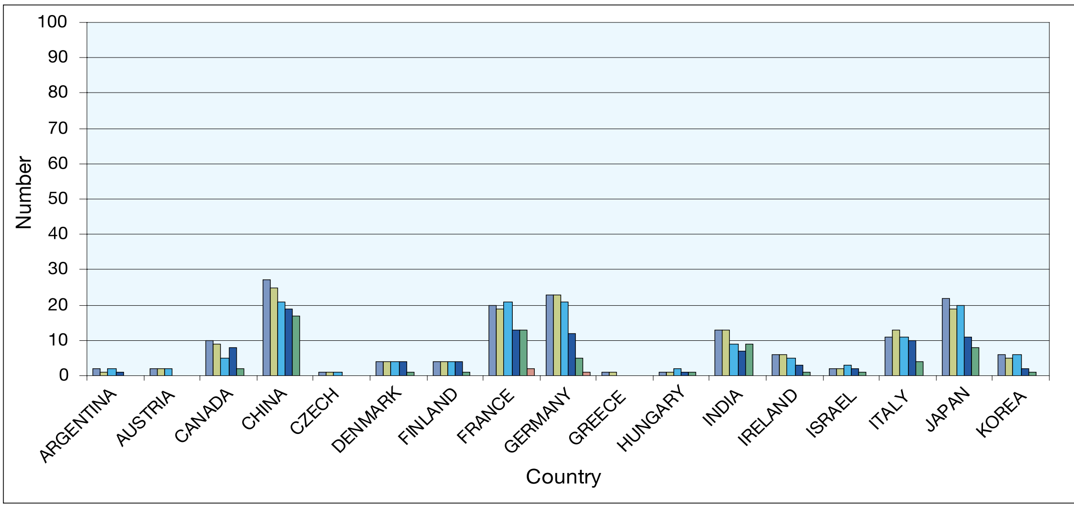



Figure 3.16 a Country-specific number of collaborations

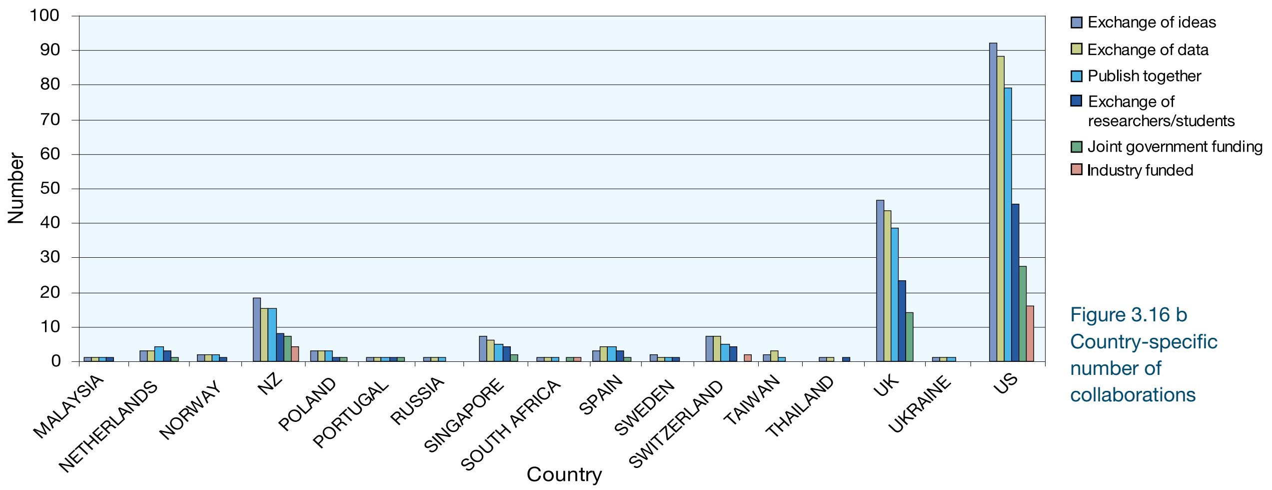



Figure 3.16 b Country-specific number of collaborations

A closer analysis of the countries for which Australia had 20 or more collaborations (standardised by the number of collaborations with that country) is provided in Figure 3.17 and this highlights some important characteristics. Firstly, that that there were no collaborations involving industry funding described for China, Japan or the UK. Secondly, that the number of collaborations involving industry funding was significantly higher for New Zealand than the percentage for all collaborations.

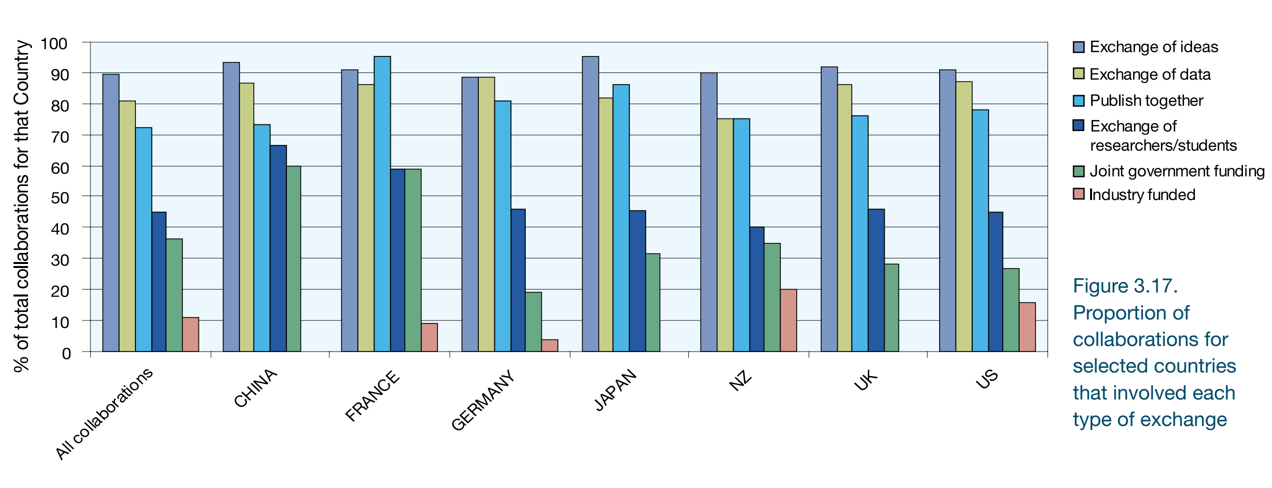



Figure 3.17. Proportion of collaborations for selected countries that involved each type of exchange

To a lesser degree this was also true for the US. There was a higher frequency of joint publications for collaborations with France, Germany and Japan relative to that observed for all collaborations. The rate of exchange of researchers and students and joint government funding was higher for China and France, whilst Germany had lower frequency of joint government funding than was observed for all collaborations. Whilst acknowledging the relatively small sample size, these slight variations for each country indicates that different types of relationships are built with each country dependent on the specific circumstances relating to that country, such as bilateral agreements and joint funding opportunities.

## 3.6 Nanotechnology networks

The vast majority of respondents were members of the ARCNN (approximately 90%) and this is not surprising given that most survey respondents were from universities (Figure 3.18). The next highest source of respondents was the ANBF which drew to a close during the seven week survey period and was therefore unable to actively participate in distributing the survey beyond an initial mail-out. Along with distribution to interested parties by network members, the existence of non-members in the mailing lists (also known as a friends list) of some of the networks most likely explains the survey respondents who reported that they were a member of none of the networks.

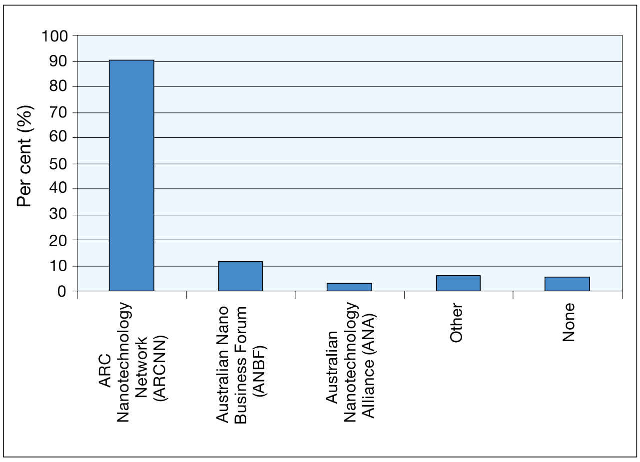



Figure 3.18. Membership of nanotechnology organisations

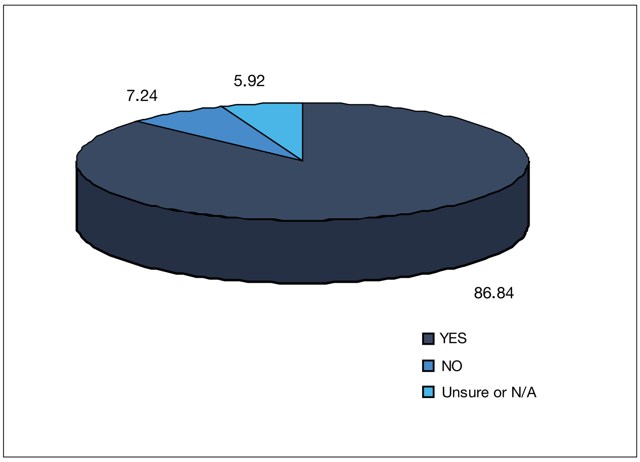



Figure 3.19. Responses to the continuation of the ARCNN as a percentage of respondents

Survey respondents were asked ‘Considering the funding for the ARCNN ends in 2009, do you see value in continuing the network?’ Over 85% of responses were positive, with a further 6% feeling that they were unqualified to comment (Figure 3.19). The remaining 7% stated that they did not see value in the continuation of the ARCNN. The comments offered by both those who supported the continuation of the ARCNN and those who did not seemed to suggest that there were varying opinions for how ARCNN funding should be focused. This was a difference in opinion on ARCNN direction and not a concern that funds had been mismanaged.

## 3.7 Broad nanotechnology issues

In considering the answers respondents provided to free-form questions the exact wording of the question is critical to understanding the concepts and ideas that were articulated, and accordingly each question and a summary of the survey participants’ responses is provided below.

### 3.7.1 What do you see as areas of strength in Australian nanotechnology?

Survey responses to this question highlighted a number of different research fields within nanotechnology but also highlighted the researchers themselves as a significant strength of Australian nanotechnology. The Australian nanotechnology community identified itself as a community, ranking its connectivity through various collaborations as one of its significant strengths. Underpinning this sense of community was the ready accessibility of research infrastructure and facilities that no single researcher could obtain. Current, high-quality training at the undergraduate and postgraduate level was considered important for ensuring the quality of Australia's future researchers. Many of the nanotechnology research fields that were identified as an Australian strength were related to materials, biology and nanocharacterisation, which matches the types of research highlighted in Figure 3.3. Alternatively, many respondents highlighted specific long-term applications such as renewable energy and medical devices, implying an awareness of the conversion of basic research into commercial outcomes. Responses to the survey suggest that Australian nanotechnology's strength is its people, whose capacity to innovate enables focus on the science of today, the development of products in response to the issues of the future, and achieving these outcomes through sharing of skills and resources.

### 3.7.2 What are the emerging trends in nanotechnology globally?

Perhaps unsurprisingly many of the research fields identified as emerging globally were within the broad categories of materials, biology and energy; the fields highlighted in this survey as being current Australian strengths (Figure 3.3 and Section 3.7.1). The detailed examples, such as quantum dots and water purification, indicate that researchers are conscious of the directions in which their own research field is developing with regard to products and commercial outcomes. Development of commercial outcomes was perceived to be possible due to the collaboration of researchers from various fields such as biology and materials science. The other emerging trend that respondents identified was the increasing emphasis on the safety of nanotechnology and the development of national and international regulation.

### 3.7.3 Describe any gaps you see in nanotechnology research in Australia?

There was significant variability in the gaps in Australian nanotechnology research that survey respondents identified but the predominant issue was commercialisation. Many respondents acknowledged that the funding, time and support necessary for the conversion of research undertaken in academic institutions into commercial products by industry was insufficient from all parties (researchers, government, funding bodies and industry). Also highlighted were issues surrounding collaboration, inadequacies in particular research fields and regulation of nanotechnology.

Several respondents were concerned about the support of collaborations both in Australia and internationally. Of particular note was concern that there were insufficient collaborations between different types of institutions, eg university and government research organisations.

With respect to regulation, responses emphasised the need for good science, good governance and engagement of the community. Community engagement was also identified as necessary for product commercialisation, to establish new markets for products containing nanotechnology. Although funding was identified as an issue by some respondents, most concerns were issues that required direction, leadership, a national strategy and long-term planning as much as direct funding.

### 3.7.4 Briefly summarise the nature of your collaborations/linkages.

Collaborations, particularly with international partners, were described as enabling access to the 'world leaders' of a particular field. The specialised skills and knowledge of the collaboration partner(s) facilitate faster project development and often involves access to facilities not available in a researcher's own institution. Through the exchange of ideas, data and staff/students, research could advance more rapidly. Survey respondents acknowledged that compatible complementary knowledge was also critical to their collaborations/linkages.

### 3.7.5 What do you regard as the impediments or opportunities to forming collaborations/linkages?

A series of interlinked issues were described as being impediments and/or opportunities for the formation of collaborations/linkages. Funding continuity was described as absolutely essential throughout various stages of collaborations, from identification to initiation to long-term maintenance. Intertwined with funding were the three interrelated issues of time, distance and opportunity. The process of developing a collaboration begins with the identification of commonalities and differences in potential contribution to a particular piece of research and this requires opportunities for exchange. Often this occurs through face-to-face meetings at venues like international conferences, attendance at which requires time. Given Australia's geographical isolation and the distances involved, particularly with respect to international events, significant funding is often necessary. Having identified a potential collaboration, a researcher will need to commit further funding to support the collaboration's development, again due to the time and/or distance involved. Alternatively researchers can utilise various communication tools (from emails through to video conferencing) to maintain the collaboration, but these can be difficult to obtain access to, are not sufficiently supported or may be inadequate. In a period when governments are increasingly concerned with the development of research into commercial outcomes, intellectual property (IP), trust and confidentiality are also concerns for many researchers. Survey respondents described funding as providing the greatest opportunity, and a lack of funding creating the greatest impediment, to overcoming the various issues that impact the development of collaborations/linkages.

### 3.7.6 Describe any benefits you have gained from participating in the ARCNN/ANBF/ANA.

Several different, generally positive, outcomes from network participation were identified by survey respondents. The networks provided information in a variety of forms, particularly newsletters and the biennial conference, International Conference on Nanoscience and Nanotechnology (ICONN). In the case of ICONN researchers identified this as an important source of knowledge of the various research projects being undertaken by other groups in Australia and internationally. Through identification of complementary research goals at ICONN researchers were able to develop collaborations which would most likely not have otherwise arisen. ICONN and other network supported conferences were seen as critical for both research field advancement and student/early-career researcher development. Network participants (from students all the way through to senior researchers) identified funding to attend conferences and/or lab visits (short-to medium-term) as another significant benefit of network membership.

The networks were seen as opportunities – to learn, to meet people, to access resources – but as with all opportunities, if not taken advantage of, then there was no benefit and consequently there were those who had not perceived a benefit from their network participation.

### 3.7.7 What suggestions do you have for improving support for nanotechnology networking in Australia?

There was significant support by survey respondents for the continuation of a network, with many additional suggestions provided on how to change and/or improve the network. Suggested additions or improvements included: stronger linkages with industry and/or international researchers; alterations in the support for student and early-career researcher conference attendance and lab visits; increased connectivity of the network through improvements in the web resources (eg lists of infrastructure and research projects); changes in the scale and/or frequency of conferences and other events; directing funding to research projects as well as, or instead of, current funding of conferences, students et cetera (note: ARC's network funding rules precluded support of research); increased public engagement; improved communication of opportunities available to network participants; and increased access to facilities. Although funding of the network was identified by many respondents as an issue, the only substantial suggestions for the long-term support of a network were industry sponsorship, continued ARC or government funding, or a membership fee. The need for a well developed national strategy was indicated by several survey respondents as being necessary to direct future Australian nanotechnology research.

## 3.8 Summary of survey data trends

Respondents to the survey held a variety of positions but the majority came from the university sector, which partly reflects the true composition of the nanotechnology community and partly reflects the method used to distribute the survey via research and business networks. Although no census data is currently available on the demographics of the nanotechnology research community, the breakdown by employer type obtained from survey respondents seems more strongly weighted towards universities than would be expected given current population estimates by nanotechnology networks. Nanotechnology population estimates predict that industry and business should represent 25 to 40% of survey respondents, rather than the 15% response rate from private, industry and service provider obtained in this study. This survey is probably a representative sample of the nanotechnology research community, which is predominantly composed of researchers from universities, but future research will need to identify additional appropriate mechanisms for obtaining a wider cross-section of views, particularly those in government research organisations and industry/business.

Nanotechnology research in Australia covers a broad range of fields, but the majority is still at the earliest stage of development. All stages of research development were described by respondents to this survey, but projects that were at the commercial stage were most likely to be undertaken by those who described themselves as directors or managers of companies, and by those who have at least six research projects. It is reasonable to expect that those involved in industry or business are more likely to have commercial products.

When describing the future directions of global nanotechnology research, survey participants identified many of the same fields that are currently strengths in Australian nanotechnology research. Applications for nanotechnology with a commercial outcome were predicted to be a future direction for nanotechnology research. This was considered possible due to the formation of cross-discipline collaborations that enable research to address specific problems. Well developed regulatory mechanisms and community engagement were identified as necessary for nanotechnology research to reach these potential commercial outcomes.

A surprisingly high number of researchers responded that they did not have any collaborators (23%), but closer analysis indicated that students were over-represented in this group, as they represented approximately 30% of the respondents but 45% of those who did not collaborate. It is to be expected that students may not yet have had the opportunity or need to develop genuine collaborations. However, the slight over-representation of those who described themselves as ‘other’ such as managers and company directors (who represented 15% of total respondents, 20% of whom did not collaborate) is of some concern and this will need to be addressed in future collaboration support mechanisms. It is possible that this group had no wish to collaborate, preferring to develop their ideas in confidence for commercial reasons. Nor would they wish to publish work which was to be commercialised. A question that was not asked in the survey, and should be included in future surveys, is ‘If you do not collaborate, why not?’. The reasons for not collaborating could then be determined.

Most of the 700 collaborations involved the exchange of ideas, the exchange of data and/or joint publication, which is not surprising given that the vast majority of collaborations were described by those from research (universities or institutes). Again, this over-representation of individuals from research could be in part due to how the survey was distributed. In the case of industry/business collaborations, issues surrounding privacy and IP may have limited the ability of some respondents to describe their collaborations (personal correspondence) leading to an under-reporting of their collaborations and/or linkages. It is of note in Figure 3.13 that like tends to be best at developing collaborations with like – government research organisations have the highest frequency of developing collaborations with government research organisations and industry/business has the highest frequency of developing collaborations with industry/business. Perhaps knowledge and understanding of each others’ structures and systems enables more ready formation of collaborations and this should be the focus of future studies. Given that most of the collaborations described involved ‘research’, it will be necessary to continue to support these collaborations but also indentify new mechanisms to better support the formation of linkages between universities/institutes and government research organisations, universities/institutes and industry/business and government research organisations and industry/business.

The collaborations described by survey participants were equally distributed between Australian and international, suggesting that the development of collaborations is based upon sourcing the best available expertise and resources for the research project whilst also acknowledging the greater accessibility of fellow Australian researchers over international counterparts.

Although it is not surprising that the majority of interactions involved the exchange of ideas, the exchange of data and/or joint publication, the limited number of collaborations involving funding, particularly industry funding, is of concern with respect to the potential to commercially leverage Australian nanotechnology research. The reported lack of industry funding for the described collaborations with China, Japan and the UK (Figure 3.17) suggests that accessing local and international industry funding will need to be a focus of future collaborations, particularly in certain global regions, in order to better leverage Australian research funding and support. A similar focus on joint government funding will be necessary with countries like Germany, for whom joint government funding was reported here as significantly below countries like Japan and New Zealand which have levels similar to the survey's average for all international collaborations.

The development of collaborations and linkages was seen as an opportunity that was dependent upon several variables, such as time, distance and ultimately funding. The geographical isolation of Australian cities and Australia relative to the global scientific community will continue to necessitate nanotechnology researchers (and researchers more generally) being strategic in their development of long-term collaborations. And whilst researchers are utilising various information and communication technologies to support their collaborations, face to face contact can only be achieved when appropriate funding mechanisms are available. As research develops towards commercial products, IP, trust and confidentiality will become even greater issues and innovative systems to deal with these issues will become increasingly necessary.

The status of the networks changed during the survey period, with the ANBF closing due to the conclusion of its government funding. The ARCNN funding is also due to end and there has been no confirmed alternative arrangement for the continued support of the network. There was support from a large number of participants for the continuation of the ARCNN network beyond 2009, with many suggestions on how to improve the focus of the network in the coming years. Of particular note was the suggestion to increase engagement with industry/business and also the international nanotechnology community. Continuation of the network will require identification of a new funding mechanism and survey respondents suggested that financial support from industry, the Australian Government (DIISR or ARC) and membership fees as possibilities. Whether any or all of these mechanisms will adequately support a nanotechnology network is unclear, but the nanotechnology research community clearly aspires to achieving more by working together according to a well articulated national strategic plan.

# 4. Nanotechnology Stakeholder Day

## 4.1 Structure of the Nanotechnology Stakeholder Day

The Australian Academy of Science hosted a one day event at the Shine Dome in Canberra on 25 September 2009 to identify the issues that impact upon or limit Australian nanotechnology research and the development of collaborations. Approximately 40 invited participants from across Australia attended from research (both universities and government research organisations), industry/business and Australian Government departments (listed in Appendix 3). A broad cross-section of attendees was selected to enable a comprehensive discussion of the issues surrounding the development of nanotechnology research in Australia.

The keynote address was presented by the director of the Singaporean Institute of Bioengineering and Nanotechnology (IBN), Professor Jackie Ying, whose biography is in Appendix 4. The morning session also included a presentation of the preliminary data and analysis of the Academy's survey. These two presentations informed discussion during the second and third sessions. Participants were divided into five groups prior to the event to distribute participants from all backgrounds across all topics. During the second session each of these five small groups were provided with one of the following topics, a copy of the slides from the presentation on the Academy's nanotechnology survey and questions relevant to their specific topic to help stimulate their group's discussions. The questions provided to each of the groups are in Appendix 5 and the topics were:

- research collaborations
- industry linkages
- international linkages
- infrastructure
- research trends.

Each group had a convener to moderate the discussion and a contracted non-participant to take notes as a record of discussions. At the end of discussions the convener and note-taker for each group developed a short presentation (the slides for which are given in Appendix 6) for the final session.

In the final session all participants were invited to engage in discussion on all of the five topics, with each convener presenting the key issues and solutions identified by their discussion group. After the presentation on each topic, participants were able to ask questions and engage in debate on the identified issues.

During the Stakeholder Day the three sessions were recorded by five non-participant scribes. The keynote address and question time was also audio recorded, with Professor Ying's permission. The keynote address recording, the scribes' notes and the slide presentations made by the discussion group conveners during the final session constitute the data collected from the Stakeholder Day.

## 4.2 Critical analysis of the Stakeholder Day data

### 4.2.1 Keynote address: *Nanostructure processing of advanced materials*

Professor Jackie Ying, director of the A*STAR and supported IBN, gave an informative presentation on several different sets of nanotechnology research being undertaken at the IBN, including the commercial applications of this research.

One set of research focused on the development of an insulin drug delivery system, in which the insulin was only released when there was an episode of hyperglycemia (high blood sugar). This targeted release was possible due to the development of a specialised glucose-sensitive polymer, which only allows release of the insulin in response to increased blood glucose. This mechanism of insulin delivery has the potential to limit the swings from episodes of hyperglycemia to hypoglycemia caused by inaccurate dosages of insulin, as it is reversible and drug release ceases once blood glucose levels decrease. Small animal studies have proven successful and the technology is now being further developed by a spin-off company, Smart Cells Inc. The company is pursuing large animal trials with the intention of developing the drug release system for human trials and ultimately commercial production.

The IBN has been similarly developing research on contact lenses with nanostructured channels for drug delivery to the eye, a nanocomposite gel that is being used as cell culture scaffold material with long-term potential for tissue replacement therapies, quantum dots for biolabelling and potentially disease detection, and novel catalysts for diverse applications such as sequestration of greenhouse gases. Although not all of these sets of research have reached commercial outcomes (although several are now being advanced by spin-off companies), the institute's research is centred on real-world problems that they are seeking to solve.

Whilst addressing Stakeholder Day participant questions, Professor Ying described how the institute is using an engineering perspective. A specific problem is considered, the institutes so called 'nanotechnology toolbox' is examined for potential solutions and, if they don't have the right tools, the IBN seeks the people and the research that will provide the necessary tools to address the problem. This ability to work with best people has in part been possible due to IBN developing memoranda of understanding with national and international universities, hospitals and companies. The Singapore Economic Development Board (EDB) has been particularly important in developing relationships with international companies. As part of these arrangements IP rights are distributed between research participants based on where the research is undertaken.

Critical to an issues- or problems-based approach to research is the commercialisation process. Professor Ying detailed how in the past ten years the IBN was constructed (as part of a greater research infrastructure program), people (staff and students) were recruited to the institute, and more than 700 patents have been filed. The marketing and commercialisation arm of A*STAR, Exploit Technologies Pty Ltd, has supported the institutes commercialisation efforts. Innovative research grants and seed funding have been critical in Singapore in developing local SMEs and SPRING Singapore (sister organisation of the EDB) has been involved in addressing this with the development of Small Business Innovative Research Grants.

To address the issue of venture capital, the Singapore government has introduced a venture-capital matching scheme and consequently the German nanotechnology investment company (Nanostart) set up its first offices outside Europe in Singapore. By providing the necessary infrastructure and skilled personnel, the IBN hopes to attract other companies to Singapore and continue to commercialise the institute's research.

### 4.2.2 Research collaborations

The first discussion group was asked to focus on the issues surrounding the development of research collaborations. During discussions the research networks such as the ARCNN were identified as having been particularly positive in developing Australian based collaborations, particularly for students. There was some debate about the benefits of different programs that the ARCNN has supported during the past five years, such as student travel or access to infrastructure, but there was strong support for the network's event, International Conference on Nanoscience and Nanotechnology (ICONN). Attending the conference was seen as an opportunity to meet potential collaborators, develop new collaborations and also maintain and strengthen existing relationships.

Although the nanotechnology research and business networks have been mostly successful, there was acknowledgement by Stakeholder Day participants that there may be a need to consolidate these nanotechnology networks in the near future. As the networks progress to a new phase it may be necessary to consider alternative organisational models, such as those used by the Australian Synchrotron. During this new phase, discussion participants considered that elements of the previous networks that were valuable, such as ICONN, should be retained and strengthened. It was felt that the individual relationships that had so successfully been developed through events like ICONN would now need to be capitalised upon, with the creation of new centres that enable a cross-disciplinary approach to specific problems, such as CoEs, CRCs and institutes. Alongside a 'market driven, problems-based' approach to nanotechnology research, Stakeholder Day participants thought there should be a strengthened focus on industry and international collaborations. It was proposed that increased visibility of collaborations that had resulted in successful outcomes, such as commercialised products, could enable increased leveraging of current funding, which will be important for the transition from the early stages of the networks to the new phase.

Discussion participants considered that a well focused strategic plan for nanotechnology research in Australia would greatly enhance the capacity of researchers to transition from the individual collaborations that have been developed to strong, interconnected collaborations that incorporated industry and/or international partners.

### 4.2.3 Industry collaborations

Stakeholder Day discussion participants were able to identify several programs that supported or facilitated the formation of linkages between researchers and industry, such as ARC-Linkage, the Enterprise Connect Scheme, Climate Ready and the Education Investment Fund. However, although some have had positive experiences with one or more of these schemes, there also seemed to be some degree of confusion about what each scheme actually supported and this was considered to have more than likely inhibited engagement of researchers with industry.

Participants described the inability of individuals from industry and research to identify each other as potential partners as having caused significant difficulties in the formation of industry-university/institute based collaborations. Ineffective communication by both industry and research of their different issues, needs and perspectives had significantly hampered the development of collaborations. This poor communication was further exacerbated by issues surrounding patenting and IP, such as costs, slow turn-around time during negotiations (particularly by universities) and equitable distribution of IP between all participants.

To improve quantity and quality of industry-university/institute linkages was described as requiring a cohesive approach that is directed by a well developed national strategic plan for nanotechnology research. Participants considered that a significant move forward would involve development of a portal where companies/industry could outline problems to which they are seeking solutions and researchers would then engage with the company if they were able to identify and offer a research solution. Such a portal could also host a more visible and centralised listing of available research facilities, researchers, the network(s) and a centralised IP database.

Another suggestion was for the development of an industry placement scheme that, unlike the current Enterprise Connect 'Researchers in Business Scheme', enabled researchers to visit multiple companies to discuss commercialisation of research.

A 'market driven, problems-based' approach to the formation of collaborations will significantly overcome some of the communication issues and may also enable identification of new industry targets for collaboration, including SMEs.

### 4.2.4 International collaborations/linkages

During discussions, participants identified a diverse array of programs that to some degree support international linkages at the individual and/or infrastructure levels. These included DIISR's International Science Linkages Program, ARC or NHMRC funded Discovery/Project Grants, ARC funded CoEs, universities (individually or as consortia), overseas funding bodies (such as the European Union), agency to agency, charities, local industry and overseas industry partnerships. Whilst by no means intended as a comprehensive list, it exemplifies the variety of support mechanisms and also highlights the complexity of these programs, as each involves different specificities and application procedures. International collaborations were acknowledged to provide a significant benefit to the Australian participants and Australia more generally through access to skills and resources that Australia does not have; accelerated progression of research; benchmarking; training; and leveraging of Australian funds.

Although international collaborations have provided significant benefit, efforts have been hampered by the decentralised approach to support and funding of international collaborations. This was considered by discussion participants as particularly true of programs that involve assessment of applications by an Australian agency and an overseas partner agency. This dual assessment process has been known to result in no applications from either country being funded due to a lack of common positive application reviews. A centralised agency that facilitates all Australian Government support of international collaborations/linkages would greatly reduce the complexity of the system and lead to significant efficiencies for applicants, assessors and the government staff administering the process. Australian participation in international research programs such as CoEs and large infrastructure were considered to need better coordination, and this too could be facilitated by the development of a single agency to direct and support international linkages. Through a single centralised agency it would be possible for Australia to develop more bilateral relationships, particularly with the hosts of large scale infrastructure. Such relationships should also include support for infrastructure access by Australian industry undertaking R&D. It was also felt that mechanisms to support interactions with international industry and business could be further developed.

Discussion participants acknowledged that low cost initiatives can and are being undertaken, that would enhance international collaborations, for example using ICT to support communication between Australian and international partners. However, these initiatives are not currently accessible in all institutions. The formation of joint training arrangements would have the positive effect of sustaining current collaborations, but also have the potential to help young researchers to develop new collaborations. Changes in these areas are underway, but need to be further developed and coordinated so that all have reasonable access. Although considered positive, the low cost initiatives described above were not considered by discussion participants to be sufficient to sustain international linkages in the long-term.

Broader engagement of the international business and industry communities through participation in international trade shows and events was also raised during discussions as a significant issue for future consideration if Australian researchers and SMEs were to engage with international business/industry.

#### 4.2.5 Infrastructure

At present several funding systems – the Education Investment Fund (EIF), the National Collaborative Research Infrastructure Strategy (NCRIS) and Linkage Infrastructure, Equipment and Facilities – support infrastructure in Australia that is critical for nanotechnology research (eg ANFF, AMMRF, Australian Synchrotron, ANSTO). Recent Australian Government focus on funding of infrastructure has resulted in current infrastructure and equipment needs being met. However, with the array of different rules attached to the different funding schemes, staffing and long-term maintenance has become a significant issue. For example EIF funds cannot be used towards staff or maintenance and there were concerns raised by Stakeholder Day participants that as funding for different facilities changes over time, that there will be cycles of expertise gain then loss. Also of concern was the lack of knowledge and understanding about the availability and capacity of infrastructure and equipment, particularly for researchers from industry who had relied on the now closed ANBF for information. Further impeding communication about the available equipment are the plethora of acronyms involved in the funding, facilities and equipment which are often unfamiliar to those in industry and business.

A portal open to researchers and industry that clearly outlined equipment access models, availability and capabilities (perhaps including case studies) was suggested to address the issues surrounding communication regarding infrastructure. Such a portal could provide information about both public and private equipment facilities (such as prototyping services and facilities) and may also alleviate some of the confusion caused by the use of a large number of acronyms.

Access models whilst currently described as adequate, except for the still developing ANFF, were an issue of concern for the future, given the uncertainty of long-term funding for facilities. Facility accessibility was considered to be particularly problematic if the ARCNN is unable to sustain support for student and early-career researcher access to infrastructure.

Adequate funding of current infrastructure support staff and equipment maintenance was considered to be by far the most significant issue. Currently approximately 50% of the ANFF's $90 million of funding obtained under the NCRIS program is used for operational costs and obviously any decreases in funding that can be used for this purpose will impact the facility's operational capacity. Future infrastructure funding mechanisms will need to address this issue if under-utilised equipment is to be avoided.

### 4.2.6 Research trends

Discussions during Stakeholder Day identified a number of fields that are a current strength of Australian nanotechnology research, and these clustered under six topics: health, materials, energy, water, metrology and OH&S. Australia currently has capability in all of these fields and it was considered inappropriate to try and select 'winners'. The networks were considered to have positively influenced the formation of collaborations and linkages, particularly across disciplines, but discussion participants considered that these networks could do more in the future if they were consolidated. The next phase of the network(s) may involve a new organisational model, such as those used in European networks, the London Technology Network or successful medical societies in Australia. In such a network(s), the development of several subgroups under the umbrella of the network facilitates dissemination of current research by disparate groups and is thought to potentially encourage further collaborations. A new organisational model could also include an annual membership fee or corporate sponsorship.

Stakeholder Day participants identified several impediments to the expansion of nanotechnology research in Australia:

- public perception and public relations;
- regulation (which is undeveloped and its future unclear);
- funding (both mechanisms and time delays);
- disconnection between different parts of the research community;
- IP; and
- university and institutional bureaucracy.

Whilst these issues are not unique to nanotechnology, the small size and emerging nature of this field provides an opportunity to address some of the issues. Given the time costs involved with administration, particularly for administering funding grants, it is not surprising that many researchers are seeking alternative sources of funding. This is particularly true of research involving international collaborations, where the 18 month turn-around time on Australian ARC and NHMRC project grants was described during discussions as a disincentive to international partners.

Also of concern to discussion participants, with regard to funding, were cross-disciplinary research projects that did not always readily sit within any single field when being assessed for funding. It was suggested that researchers need to position themselves relative to the problems of industry/business, international governments or international companies to access alternative funding sources.

The complexities and costs of IP were again identified as an impediment to collaborations and ultimately the commercialisation of research. Mechanisms for technology transfer such as those outlined by Professor Ying for Singapore or alternatively mechanisms in place in France or at the Max Planck Institute in Germany were suggested as potential models for nanotechnology transfer and commercialisation in Australia. As with funding, it was suggested that the focus of researchers needs to be transferred to the needs of the market and that a strong national nanotechnology research strategy would facilitate this.

## 4.3 Discussion trends

Professor Ying provided an informative introduction to the potentials of nanotechnology and an insight into how Singapore has set up the structures necessary to develop research capacity and the capability to produce commercial outcomes. Many of these support mechanisms could play a role in the commercial development of Australia's nanotechnology research, particularly government support mechanisms and seed funding for the development of local spin-off companies.

Although each of the discussion groups was focused on a different topic there was a surprising convergence in the trends, issues and solutions identified. The networks were recognised as having significantly supported both the research and industry/business nanotechnology communities. Current changes in the number and funding of these networks provide an opportunity to assess their successes and identify where improvements could lead to future success. Many participants believe that the consolidation of the various nanotechnology networks would strengthen the individual participants of the nanotechnology community. This would necessarily require changes in some systems and organisational structure, but by focusing on the success stories of the entire sector it could be possible to significantly leverage funding.

As part of this new centralised nanotechnology community one significant resource would be an internet resource portal. Such a tool would incorporate a section where industry can describe a particular technological problem they are attempting to solve and researchers suggesting solutions to these market-driven problems, resulting in the development of industry-university/institute linkages. This website could also include listings and information about research infrastructure and equipment (public and private), scientists' current research and a centralised IP database. A well supported, web-based resource open to both research and industry/business could significantly overcome many of the communication difficulties that have arisen between the disparate parts of the nanotechnology community.

Also aimed at improving communication between industry/business and nanotechnology researchers would be the development of a scheme that enabled researchers to undertake visits or placements in multiple companies to promote particular research.

Centralisation of the various programs that support the formation of international science linkages was strongly recommended. The benefits that Australia receives from its participation in international collaborations/linkages could be further leveraged if the support mechanisms within Australia were simplified, were better integrated with external/international support mechanisms and completed in a more efficient time frame. A centralised agency could also support existing and new bilateral and multilateral partnerships, advocate for Australian involvement in international infrastructure and also facilitate greater interaction with international industry and businesses.

Technical staffing and maintenance of Australian nanotechnology infrastructure and equipment is not adequately addressed under current infrastructure funding mechanisms and this is of great concern to the research community. Researchers want to avoid significant, current Australian Government investment in infrastructure and equipment being under-utilised due to a lack of trained staff or long-term maintenance. It was therefore strongly recommended that all future infrastructure and equipment funding incorporate support of staff and maintenance costs at a rate at least comparable to those currently in use. For example ANFF spends approximately 50% of current NCRIS funding on operational costs, including the creation of 30 skilled jobs.

It was proposed that a proportion of funding for Australian nanotechnology research be re-orientated to towards ‘market driven, problems-based’ research. Research that focuses on market-driven problems has the potential to greatly increase funding opportunities, beyond those currently available through Australian Government granting schemes.

The transition from a decentralised series of networks to centralised system that incorporates both basic research and ‘market driven, problems-based’ research, which links well with industry and strongly connects with the international community, will occur more rapidly and with greater impact if directed by a ‘National Strategic Plan for Nanotechnology Research’. Meetings such as the Stakeholder Day provided the nanotechnology community with the opportunity to draw together ideas from the disparate groups and move towards a united nanotechnology community. Future meetings would help to facilitate the development of a national strategic plan for nanotechnology research and ultimately a strong, well integrated nanotechnology community.

# 5. Australian nanotechnology research today and into the future

## 5.1 Current nanotechnology research in Australia

Bibliometric data on Australian publications in the field of nanotechnology and data collated during the Academy's survey of the Australian nanotechnology researchers indicates that research is strong across a variety of sub-disciplines and is continuing to grow at a rapid rate (6 to 7% increase in publications per year). Much of the research being undertaken and published by Australian nanotechnology researchers is at the basic and/or applied level of development, which is to be expected given the strong role of universities in Australia's innovation sector.[16] A small number of research projects were described as having been developed to commercial production and this was mostly by people in management or director positions within companies, rarely by researchers who described themselves as student, staff or group leader. Such a strong demarcation between basic research undertaken in universities and the commercial production of technologies by industry/ business has been recognised as an issue across the Australian innovation sector.[17] This divide will need to be bridged in the near future to increase the frequency and speed with which basic research is developed into commercial outcomes if nanotechnology is to achieve outcomes similar to those observed for other successful technologies such as ICT.

The Academy's survey data on Australian nanotechnology researchers indicated that currently there are only slightly fewer Australian based collaborations than international collaborations. However, bibliometric data shows that Australian-only authored publications (all science and nanotechnology) have significantly declined. Whilst this indicates Australian nanotechnology research is increasingly and solidly integrated with the international community, it is important that collaborations between Australian nanotechnology researchers continue to be supported so that improvements in Australia's nanotechnology research capabilities continue to be made and that current capacities are not wasted.

Early-career nanotechnology researchers are particularly vulnerable to structural changes, for example currently one of the major support mechanisms for the development of early-career collaborations is through the travel funding and events of the ARCNN. Foreshadowed changes in the funding of the ARCNN have the potential to dramatically decrease the development of new and independent collaborations by students and early-career researchers. This will have significant long-term consequences for the growth of the nanotechnology field.

The collected data indicated that Australian scientific researchers, particularly nanotechnology researchers, have been developing international collaborations and linkages, which have resulted in an increasing number of publications with both Australian and international authors. This is also strongly supported by the existence of collaborations that currently involve the exchange of ideas and data, but may in the future develop into outputs such as joint publications and/or patents. Although these metrics indicate that international collaborations are currently well supported, significant concerns were raised by participants of the Stakeholder Day about the lack of strategic support for, and coordinated funding of, international collaborations. Considered to be particularly alarming was the uncertainty of the continuation of existing ad hoc support mechanisms.

Nanotechnology researchers have developed strong collaborations involving the exchange of ideas, exchange of data and joint publications at the local and international levels but there has been far less development of collaborations involving joint funding, particularly industry funding. The need for more integration between universities, research institutes, government and industry/business was identified in the survey and was amongst the issues identified and discussed by Stakeholder Day participants. Although not specific to the nanotechnology field, there is the potential with this vibrant and growing area of research to address some of the issues that lead to segregation of the different sections of the innovation process. There is the potential to improve the integration of universities, government and industry/business, and consequently increase industry/business funding of research, through a stronger focus on 'market driven, problems-based' research and strengthened support of collaboration at the Australian and international scale. However, existing government initiatives to support linkages between industry/business and the basic research community were considered varied in success by Stakeholder Day participants. The recognition by survey respondents and Stakeholder Day attendees of the need to improve communication with industry/business positions them well to identify and act upon new strategies to support increased interaction.

IP and the need for science-based regulation were both seen as critical forthcoming issues. In the case of IP, the participants noted that disparate and often dysfunctional IP services of universities were hindering the development of research into commercial outcomes. Researchers often found that dealing with IP became highly time consuming, and consequently were discouraged from developing partnerships with industry/business. Competing time and output demands on researchers lead to their avoidance of IP-related issues. Consequently, research is impeded from being developed to its full commercial potential. Although not a specific focus of this research, participants in this study highlighted the need for further engagement with the government to support the development of science-based regulation.

## 5.2 Visions for the future of nanotechnology research in Australia

There was general recognition of the need for research to move more easily through the various stages of development towards a commercial outcome. It was suggested that a redirection in funding may be necessary to shift some research to a 'market driven, problems-based' focus, which could significantly increase the development of research from basic to applied, through various testing phases to commercial production. To quote one participant:

> We need to identify the research problems which will really concern industry, eg carbon trading. The financial aims will become significant to industry.[18]

A 'market driven, problems-based' focus would encompass issues as broad as climate change, energy and water; or as specific as the need to improve the quality of a single industry product or manufacturing process. Although commercial product development utilising nanotechnology would be a goal of this approach, there would also be a flow-on effect of increasing and broadening support for basic research through expanded opportunities for accessing alternative funding sources.

Whether through new networks or existing funding agencies, funding mechanism(s) for Australian based collaborations and linkages need to be identified and secured long-term. The benefits of collaborations are recognised[19] and include leveraging, acceleration of research, access to complementary skills and/or infrastructure. The distances between Australian cities necessitate a strong support system for both face-to-face communication and also lower cost IT communication tools, for example video conferencing. Communication opportunities are essential to the success of collaborations and will need ongoing support if current, as well as new, collaborations are to be developed and maintained in the future.

Recognising that ongoing support of international collaborations remains precarious, participants suggested that a single centralised program to support and administer international collaborations/linkages at all scales, from individual visits through to large-scale infrastructure, would be of significant benefit. A centralised agency would have the benefits of reduced administration, potential improvements to assessment processes (including turn-around times between applications and funding approval) and consequent increased leveraging of available funds due to increased ability to attract co-investigators and other funding partners.

One of the largest issues identified was communication between industry and the other members of the nanotechnology research community. The multiple nanotechnology networks have been an important part of the development of nanotechnology research over the last decade but the networks were oriented either towards researchers or industry/business and these disparate networks have not previously been well integrated. Due to a convergence of circumstances and growth of the Australian nanotechnology sector over the last decade there is now an opportunity to draw together the resources and capacities of the various networks. Such a move would require support from across the nanotechnology research sector, significant changes in the structures of the networks and the development of new aims that support all sectors of nanotechnology research in Australia. Stakeholder Day participants in particular, given the diversity of their backgrounds, recognised the critical need for increased unity between all parts of the sector if they are to continue to seek funding, support and also expand. It was acknowledged that the various networks had been appropriate and productive in the past but that the sector had evolved to the extent that its needs had changed. The strong desire to better integrate basic research with commercial outcomes may result in a single network being more efficient at providing services to the entire nanotechnology community.

As part of a restructuring of the nanotechnology networks it was proposed that an interactive, well-structured online resource would greatly improve communication and cross-sector knowledge. Such a resource would require full-time staff to develop and manage it. It was proposed that an online resource be made available to industry members, allowing them to post a particular problem to which they are seeking a solution; researchers would then be able to assess the problem and provide open and/or confidential feedback to the poster on potential solutions. The industry and research partners having identified a potential problem-solution pairing could then go on to develop a collaboration. Such a system would go on to address one of the critical issues of potential collaboration identification. A database describing current research projects, investigative trends and research capabilities would further enhance this process of identifying potential collaborators by providing industry with better insight into potential business solutions or opportunities.

A complimentary researcher visit or placement scheme that funded a researcher to spend up to a year presenting their research to appropriate potential industry/business partners could also enhance communication between researchers and industry/business.

Complications in applying for and protecting IP have become an increasing problem for researchers in institutions that do not have well developed systems in place, particularly some universities. An Australian nanotechnology IP database that is easy to navigate would help to reduce research duplication. The IP resource could be extended to include support for researchers within universities and research institutions in the process of applying for patents.

This online resource could also be developed to support the recent federal and state government investments in infrastructure and equipment by providing wider knowledge of available resources, including access models, availability and capabilities. Although a listing of available university and research institute infrastructure and equipment currently exists through the ARCNN website, knowledge of this resource amongst the industry/business research community is quite variable and is predicted to decrease with the loss of the ANBF. A new resource would also have the potential to provide information about equipment available within industry that is accessible to external researchers. The relatively small size of Australia's research community and the geographical isolation of Australia's major cities necessitate effective sharing of available resources to avoid unnecessary duplication or loss of research projects to overseas competitors due to lack of knowledge of available resources.

## 5.3 Recommendations to support the future development of Australian nanotechnology research

The data collected during the bibliometrics and the survey created a more detailed picture of the current status of nanotechnology in Australia. Australian nanotechnology researchers are part of a vibrant, growing research community, with work being undertaken across a number of subdisciplines. The connection between universities (with basic and applied research) and industry/business (with commercial production) appears to be underdeveloped. This disconnection stands to be addressed if nanotechnology in Australia is to reach its full research and commercial potential. Changes in circumstance for support of international collaborations/linkages and the support of the various nanotechnology networks have arisen as current concerns and challenges. For nanotechnology to continue to develop as a quality Australian research discipline, that is well integrated locally and successfully accessing international nanotechnology capabilities and markets, specific action is required in the near future on the part of universities and institutes, industry and government.

The following prioritised recommendations were developed from the ideas that the nanotechnology community itself identified as solutions to current impediments for their continued growth and expansion as a contributor to technology development and implementation.

## Recommendations

### Recommendation 1

Australian Government should lead the production of a National Strategic Plan for Nanotechnology Research that is developed in consultation with the research community from universities, government research organisations, Australian industry/business, as well as other key stakeholders (eg state and territory governments).

### Recommendation 2

Long-term funding should be allocated by the Australian Government to an integrated nanotechnology network that simultaneously represents research and industry needs and is supported according to typical innovation development time frames, ie ten years. The network participants would be instrumental in the development and implementation of:

- The National Strategic Plan for Nanotechnology Research (Recommendation 1); and
- An appropriately funded online resource that includes:
  - mechanisms to promote discussion between industry and basic researchers;
  - lists of available nanotechnology infrastructure and equipment;
  - lists of current research and researchers; and
  - a database of intellectual property.

### Recommendation 3

Develop a single, centralised, national support mechanism for international collaborations and linkages at all scales which improves the timeliness (three month turnaround) and simplicity of the application process, administration processes and decision making.

### Recommendation 4

In the short-term the federal, state and territory governments should identify and allocate funding for the ongoing costs of existing nanotechnology infrastructure and equipment, and in the long-term incorporate operational costs, such as maintenance and provision of technical staff, into infrastructure funding models.

### Recommendation 5

Funding agencies, while continuing to support basic research in nanotechnology, should orientate some support and funding towards encouraging ‘market driven, problems-based’ research.

### Recommendation 6

The Australian Government should establish, perhaps as part of the Commonwealth Commercialisation Institute, a nanotechnology entrepreneurial fellowship scheme that enables scientists to undertake placements with multiple members of industry to disseminate and foster particular sets of research for commercialisation.

### Recommendation 7

Federal, state and territory governments should maintain support and funding mechanisms for Australian-based nanotechnology collaborations, with dedicated schemes for postgraduate students and early-career researchers.

### Recommendation 8

Federal, state and territory governments should continue already successful efforts to integrate with research, industry and business in the development of science-based regulation and direct community engagement on nanotechnology issues.

# Abbreviations

| | |
|---|---|
| AMMRF | Australian Microscopy and Microanalysis Research Facility |
| ANA | Australian Nanotechnology Alliance |
| ANBF | Australian Nano Business Forum |
| ANFF | Australian National Fabrication Facility |
| ANSTO | Australian Nuclear Science and Technology Organisation |
| ARC | Australian Research Council |
| ARCNN | Australian Research Council Nanotechnology Network |
| CoE | Centres of Excellence |
| CRCs | Cooperative Research Centres |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation |
| DIISR | Department of Innovation, Industry, Science and Research |
| ECR | Early-career Researcher |
| EIF | Education Investment Fund |
| IBN | Institute of Bioengineering and Nanotechnology |
| ICONN | International Conference on Nanoscience and Nanotechnology |
| ICT | Information and Communication Technologies |
| ISL | International Science Linkages |
| LIEF | Linkage Infrastructure, Equipment and Facilities |
| NBS | National Biotechnology Strategy |
| NCRIS | National Collaborative Research Infrastructure Strategy |
| NETS | National Enabling Technologies Strategy |
| NHMRC | National Health and Medical Research Council |
| NNS | National Nanotechnology Strategy |
| OECD | Organisation for Economic Co-operation and Development |

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# Appendices

## Appendix 1
## Bibliometric analysis Boolean strings

### String 1 (nano-scale)

nano* NOT nanomol* NOT nanosec*

### String 2 (nano-tools and techniques)

atom* force microscop* OR scanning tunnel* microscop* OR scanning probe microscop* OR scanning force microscop* OR electron beam lithography OR EBL OR molecular beam epitaxy OR MBE OR atomic layer deposition OR ALD OR metal*organic chemical vapor deposition OR MOCVD OR focused ion beam* OR FIB

### String 3 (self-assembly and molecular-scale)

self*assembl* OR self organized growth OR self organised growth OR molecul* assembl* OR molecular wire* OR molecular switch* OR molecul* manipulat* OR molecular motor* OR atom* manipulat* OR fulleren* OR colloid* particle* OR molecular siev* OR mesopor*

### String 4 (nanoelectronics)

quantum dot* OR quantum array* OR quantum device* OR quantum wire* OR quantum computer* OR quantum well* OR molecular electronics OR quantum size effect* OR molecular comput*

### String 5 (nanobiology)

DNA comput* OR biomim* OR molecular template* OR molecular recognition OR biocompatible membrane* OR biocompatible surface modification* OR biosensor* OR biochip*

### String 6 (nanomedicine)

drug delivery OR drug carrier* OR drug targeting OR diagnostic sensor* OR Protein delivery OR ((immobiliz* OR immobilis*) AND (DNA OR template* OR oligonucleotide* OR polynucleotide*))

## Appendix 2

## Survey of Australian nanotechnology research trends and collaboration networks

Answers to fields or questions marked with a * were required.

### Personal details

1. Name* ...................................................................................................................................

2. What type of position do you hold?*

   student, staff, group leader, other (please specify)

   ...................................................................................................................................

3. Institution* ...................................................................................................................................

4. What type of institution is this?*

   university, government, private, industry, service provider

5. Email address* ...................................................................................................................................

### Part I – Nanotechnology research trends

6. Which of the following categories describes your nanotechnology or nanoscience? (Select as many as are appropriate.)*

   materials, nano-biotech or medical devices, energy & environment,
   electronics & photonics, quantum technology, nanocharacterisation,
   simulations & modelling, other (please specify)

   ...................................................................................................................................

   ...................................................................................................................................

7. At what stage of development is your research? (Answer for each of your current projects, up to a maximum of six projects.)*

   basic research, applied research, development, preliminary trials, later-stage trials,
   pre-commercial, commercial production

### Part II – Collaborations by Australia's nanotechnologists

8. Do you have collaborations or linkages with any other research group, industry partner or organisation?*

   Yes / No

9. If yes, please list the names of your top 10 collaborators (outside your own institute/organisation) by the group leaders name, their institution and the country in which they are located. For example, Professor John Smith, NZ Polytech, New Zealand. (Note: this information will stay confidential and only general, collated information will be publicly reported.)

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10. For each collaborator/linkage indicate which of the following is involved (select as many as are appropriate).

    exchange of ideas, exchange of data, publish together, exchange of researchers/students, joint government funding, industry funded

11. Briefly summarise the nature of your collaborations/linkages.*

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12. What do you regard as the impediments or opportunities to forming collaborations/linkages?*

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## Part III – Emerging trends in nanotechnology

13. What do you see as areas of strength in Australian nanotechnology?*

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14. What are the emerging trends in nanotechnology globally?*

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15. Describe any gaps you have seen in nanotechnology research in Australia.

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## Part IV – Nanotechnology networks in Australia

16. Are you a member of any nanotechnology network organisations?*

    ARC Nanotechnology Network (ARCNN), Australian Nano Business Forum (ANBF), Australian Nanotechnology Alliance (ANA), other (please specify)

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17. Describe any benefits you have gained from participating in the ARCNN/ANBF/ANA.

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18. Considering that the funding for the ARCNN ends in 2009, do you see value in continuing the network?

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19. What suggestions do you have for improving support for nanotechnology networking in Australia?

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## Appendix 3
## Stakeholder Day attendees

Dr David Abbott
Dr Phil Aitchison
Dr Miles Apperley
Dr Andrew Campitelli
Professor Frank Caruso
Professor Richard Coleman
Professor Mike Cortie
Dr Michael Esler
Dr Evan Evans
Professor Laurie Faraone
Dr Thomas Faunce
Dr Cathy Foley
Ms Carla Gerbo
Professor John Justin Gooding
Ms Vanessa Heuser
Ms Rosie Hicks
Professor Andrew Holmes
Dr Leo Hyde
Professor Chennupati Jagadish
Dr Michael James
Dr Craig Johnson
Professor Deborah Kane
Dr Cameron Kepert
Dr Abid Khan
Mr Brett King
Mr Conor Martin
Ms Caroline Mills
Professor Tanya Monro
Professor Paul Mulvaney
Dr David Owen
Professor Steven Prawer
Dr Jeanette Pritchard
Professor Colin Raston
Dr Christine Scala
Dr Michael Selgelid
Dr Joseph Shapter
Professor Michelle Simmons
Professor Matt Trau
Professor Gordon Wallace
Dr Alan Wilson

## Appendix 4
## Keynote speaker biography

### Professor Jackie Ying biography

Jackie Ying was born in Taipei, raised in Singapore and New York, and graduated with BE summa cum laude in chemical engineering from The Cooper Union in 1987. As an AT&T Bell Laboratories PhD Scholar at Princeton University, she began research in materials chemistry, linking the importance of materials processing and microstructure with the tailoring of materials surface chemistry and energetics. She pursued research in nanocrystalline materials with Professor Herbert Gleiter at the Institute for New Materials in Saarbrücken, Germany, as NSF-NATO Post-doctoral Fellow and Alexander von Humboldt Research Fellow. Professor Ying has been on the Chemical Engineering faculty at Massachusetts Institute of Technology (MIT) since 1992, and was promoted to associate professor in 1996 and to professor in 2001. She is currently the executive director of the Institute of Bioengineering and Nanotechnology (IBN), Singapore, and an adjunct professor of chemical engineering at MIT. IBN is a new multidisciplinary national research institute founded in March 2003 to advance the frontiers of engineering, science and medicine; it has grown to over 190 research staff and students under Professor Ying's leadership. Its mission is to conduct research at the interface of bioengineering and nanotechnology. By creating a knowledge base that bridges between molecular sciences and nanotechnology, IBN seeks to create novel nanostructured materials, devices and systems with unique functionalities and commercialisation potential for biomedical applications.

Professor Ying's research is interdisciplinary in nature, with a theme in the synthesis of advanced nanostructured materials for catalytic, ceramic and biomaterial applications. Her laboratory has been responsible for several novel wet-chemical and physical vapour synthesis approaches that create nanocomposites, nanoporous materials and nanodevices with unique size-dependent characteristics. These new systems are designed for applications ranging from the production of fine chemicals and pharmaceuticals, the efficient use of energy and resources, the control and prevention of environmental pollution, the targeted delivery of drugs, proteins and genes, to the generation of biomimetic implants and tissue scaffolds. Professor Ying has authored over 250 articles, and presented over 270 invited lectures on this subject at international conferences.

Professor Ying has been recognised with a number of research awards, including the American Ceramic Society Ross C Purdy Award for the most valuable contribution to the ceramic technical literature during 1993; the David and Lucile Packard Fellowship; the Office of Naval Research Young Investigator Award; the National Science Foundation Young Investigator Award; the Camille Dreyfus Teacher-Scholar Award; the Royal Academy of Engineering ICI Faculty Fellowship; American Chemical Society Faculty Fellowship Award in Solid-State Chemistry; the Technology Review TR100 Young Innovator Award; the American Institute of Chemical Engineers (AIChE) Allan P Colburn Award for excellence in publications; the World Economic Forum Young Global Leader; and the Chemical Engineering Science Peter V Danckwerts Lectureship. She was elected a member of the German National Academy of Sciences, Leopoldina, in 2005 and is currently the youngest member of the academy. She was named as one of the One Hundred Engineers of the Modern Era by AIChE in its Centennial Celebration, and was recently honoured with the Great Woman of Our Time Award for Science and Technology by *Singapore Women's Weekly*.

Professor Ying serves on the advisory board of the Society for Biological Engineering. She was appointed by the US National Academy of Engineering in 2006 to serve on the blue-ribbon committee that identifies the grand challenges and opportunities for engineering. She was also recently appointed to the scientific advisory board of Molecular Frontiers, a global think tank that promotes molecular sciences. Professor Ying has actively engaged her discipline with the frontiers of inorganic materials as the Materials Engineering and Sciences Division Director of the AIChE, and organised the Topical Conference on Advanced Ceramics Processing at the 5th World Congress of Chemical Engineering. She plays a leading role in the field of nanostructured materials, chaired the US Department of Energy Workshop on Future Research Needs of Nanofabricated Materials (1994), and organised the Third International Conference on Nanostructured Materials (1996), the Engineering Foundation Conference on Processing and Properties of Nanostructured Materials (2000), the first, third and fifth Society for Biological Engineering International Conference on Bioengineering and Nanotechnology (2004, 2007, 2010), the second Molecular Frontiers Symposium (2008), and the first Nano Today Conference (2009).

Professor Ying is the editor-in-chief of *Nano Today*. She is advisory editor for *Materials Today* and *Molecular and Supramolecular Science*, and serves as editor and on the editorial board of numerous journals. She served on the international advisory board of University of Queensland Nanomaterials Centre (Australia), the National Research Council Steacie Institute for Molecular Sciences (Canada), and the Leibniz-Institut für Festkörper- und Werkstoffforschung Dresden (Germany), and the board of directors of Alexander von Humboldt Association of America. She is an honorary professor of Jilin University (China) and Sichuan University (China), and an adjunct professor of National University of Singapore and Nanyang Technological University (Singapore). Professor Ying has over 120 patents issued or pending, and has served on the advisory boards of six start-up companies and a venture capital fund.

### Keynote address: *Nanostructure processing of advanced materials*

Audio for this presentation is available from www.science.org.au/reports

## Appendix 5
## Questions provided to Stakeholder Day discussion groups

The five discussion groups were allocated pre-event to evenly distribute expertise and then each group was located in separate rooms. Each group was provided with the following instruction and their topic specific discussion questions:

> Below are a list of points and questions to consider during your discussions. In no way are you limited to these discussion points, rather they are intended to stimulate conversation.

Each group had a convener, a non-participant scribe and one and half hours discuss their allocated topic before returning to continue discussions with all attendees.

### Research collaborations

- What is the current support for collaborations between researchers?
- What impediments or deficiencies are there in the support of collaborations?
- Are there any differences between nanotechnology collaborations and collaborations in other research areas
- Should, and if so how, collaborations between researchers be supported?
- What low- or no-cost initiatives can researchers and their institutions undertake to improve researcher–researcher collaborations?
- Given that the ANBF has ended and the ARCNN's future funding is unclear, what do you think will be needed to build and maintain Australia's nanotechnology community?
- Have the networks (ARCNN, ANBF, ANA) assisted in the development of NEW collaborations?

### Industry collaborations and linkages

- How are industry linkages with researchers or industry partners currently supported?
- What are the impediments to industry–researcher and industry–industry collaborations?
- Consider IP, limitations on expenditure of grant funding
- What mechanism would you recommend to increase the number and the quality of industry linkages with researchers and/or industry?
- What low- or no-cost initiatives can researchers, their institutions and industry/business undertake to improve collaborations?
- Given that the ANBF has ended and the ARCNN's future funding is unclear, what do you think will be needed to build and maintain Australia's nanotechnology community?
- Have the networks (ARCNN, ANBF, ANA) assisted in the development of NEW collaborations?

## International collaborations

- What are the current mechanisms to support different types of international collaborations (individual researchers versus participation in large infrastructure)?
- Are these support mechanisms sufficient? Describe why or why not.
- How could the current support mechanisms be improved and what would the expected outcomes be of these changes?
- What low or no cost initiatives can researchers and their institutions undertake to improve international collaborations?
- How could Australian researchers be better accessing overseas nanotechnology networks?
- Have the networks (ARCNN, ANBF, ANA) assisted in the development of NEW collaborations?

## Infrastructure

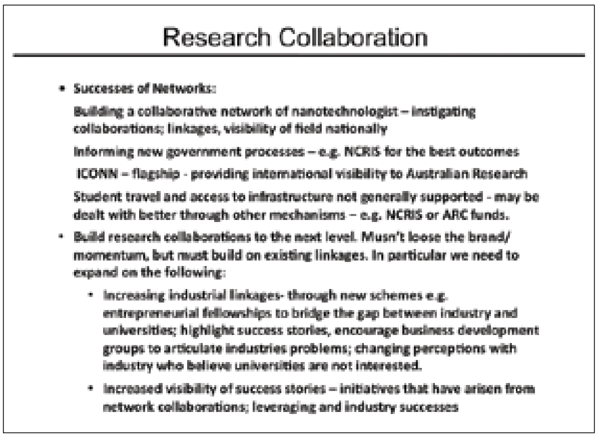
- What is the status of nanotechnology infrastructure in Australia?
- Is there any large scale infrastructure needed that requires a coordinated, strategic approach? Describe.
- Are there any other gaps in nanotechnology infrastructure?
- What low- or no-cost initiatives can researchers and their institutions undertake to meet the current and future infrastructure needs of the entire nanotechnology community?
- Given that the recently announced EIF funding of infrastructure cannot be applied to salary or other ongoing running costs, what issues do you see around the continued support of nanotechnology infrastructure?

## Research trends

- Given the findings of the Academy's nanotechnology survey, Australia seems to have a broad research base in nanotechnology. Do you think this is an accurate description of Australian nanotechnology?
- What do you think are the future directions for nanotechnology research in Australia?
- In which nanotechnology fields is Australia best placed to become (and sustain) a position of world leadership?
- What impediments do you see for the continued development of the nanotechnology research community?
- What can the nanotechnology community do towards maintaining competency across current and emerging nanotechnology research fields?
- Are there areas of nanotechnology research that Australia should not pursue?
- Given that the ANBF has ended and the ARCNN's funding will soon end, what do you think will be needed to build and maintain Australia's nanotechnology community?

# Appendix 6
# Presentations from Stakeholder Day

## Research collaborations



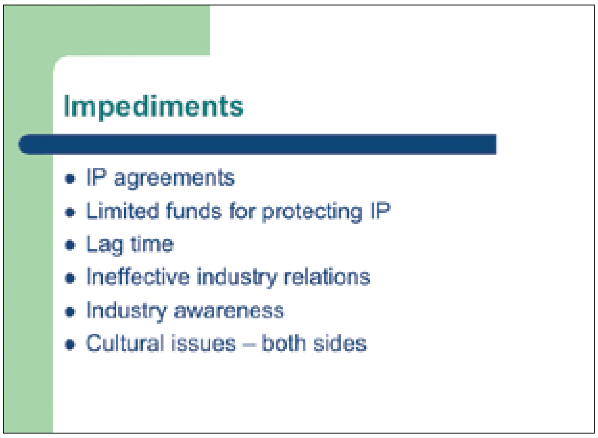

Slide 1


Slide 2

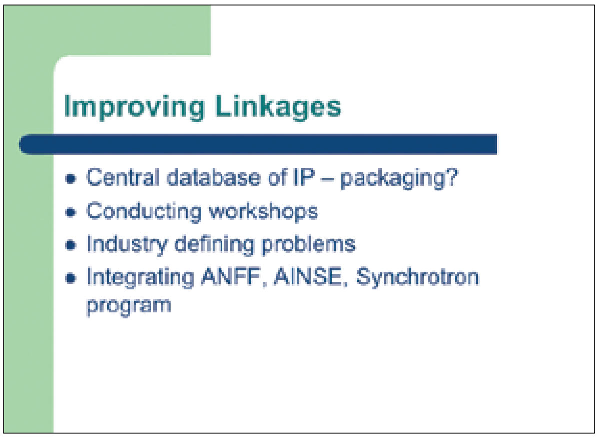
## Industry linkages


Slide 1


Slide 2




Slide 3




Slide 4


Slide 5

## International linkages

### International Collaborations

Slide 1

### Survey

- Individual linkages - 700 from 75% respondents 25% alone
- Research to research
- Ideas, data, publishing
- Larger number of int than Aus
- USA UK China DE FR JP over 20 countries

Slide 2

### Networks

- 90% ARCNN
  - 2009 post continuation - 83% yes; 7% no
  - Funds better spent elsewhere
- ANBF 10%

Slide 3

### Current mechanisms

•DIISR ISL
–Network, general, targeted, specific researcher
•Other Government Departments
•ARC/NHMRC
Existing Discovery/Project Grants/CoE
•University consortia led
•Overseas Agencies include EU
•Agency to Agency
•Charities
•Local industry
•Overseas industry partnerships

Slide 4

### Current mechanisms for international support

Individual researchers
see previous slide

Participation in large infrastructure

Slide 5

### Collaboration for collaboration's sake Y/N

- To complement existing skill sets
- Acceleration through global strategic partnerships
- Leverage based on synergies
- Value for money
- Benchmarking
- Training

Slide 6

## International linkages

### Are current mechanisms sufficient?

NO

Decision-making mechanisms are not coordinated with international funding sources

Each partner should jointly decide funding outcome

Slide 7

### Improvement in current support

*Mechanisms*

Coordinated decision making essential

International CoE

International doctoral training networks

One central international agency

Slide 8

### Expected outcomes

- Joint publications
- Joint patents
- Leverage of funding
- Joint product development
- Jointly supervised students
- Number of person days in exchange
- Destinations
- Revenue

Slide 9

### Low cost initiatives

- Teleconferencing
- Internet exchange
- Joint degrees
- Joint appointments
- Joint training programs

Slide 10

### Engaging overseas networks/ infrastructure

- Establish formal bilateral partnerships with major organisations in the world
- Establish experimental infrastructure access fund (seed funding)
- Facilitate similar access for industry (seed experiments)

Slide 11

### Influence of ARCNN, ANBF ANA in new collaborations?

- ICONN has provided a strong opportunity for new collaborations

Slide 12

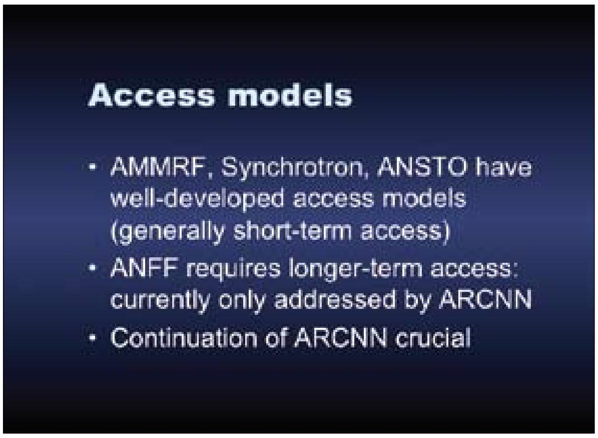
## Infrastructure


Slide 1


Slide 2


Slide 3


Slide 4




Slide 5

## Research trends

**Blue Session: Research Trends**

**Q1: Given the findings of the Academy's nanotechnology survey, Australia seems to**
**Have a broad research base in nanotechnology. Do you think this is an accurate**
**Description of Australian Nanotechnology?**
A1: Yes, though questions about strength, depth and co-ordination need to be Accounted for. Also, some question about lone academics presenting an artificially inflated picture.
**Q2: What do you think are the future directions for nanotechnology research in Australia?**
A2: Several key fields:
• Nanomedicine
• Printable PVs
• Energy
• Water
• I.T.
• Composites/Polymers/Materials
• High Temperature Superconductors
Overall, biggest areas likely to be:
• OHS/ Regulation
•Nano-metrology

Slide 1

**Blue Session: Research Trends**

**Q3: In which nanotech fields is Australia best palced to become (and sustain) a position of world leadership?**
A3: Several again:
• Sensing Devices
• PVs
• Particles/Polymers/Materials

**Q4: What impediments do you see for the continued development of the nanotech research community?**
A4: Several key areas:
• Regulation
• Public Perception
• Government Labs Vs Uni system – differing structures
• I.P. – Translation to Commercialisation
• Risk and understanding risk culture
• Lack of supporting infrastructure in external industry, companies
• Bureaucracy
• Funding Structures and time delays inherent.
• Lack of information/ education/ public relations exercises.

Slide 2

**Blue Session: Research Trends**

**Q5: What can the nanotech community do towards maintaining competency across current and emerging nanotech research fields?**
A5: All of the above???

**Q6: Are there areas of nanotechnology research that Australia should not pursue?**
.A6: Far too early to tell; one's options must remain very mush open.

Slide 3

**Blue Session: Research Trends**

**Q7: Given the ANBF has ended and the ARCNN's funding will end soon what do you think will be needed to build and maintain Australia's Nanotech community?**
A7: Several again:
• Re-fund the ARCNN
• Profits from conferences
• Membership fees to sustain
• Further conferences and international links
• Corporate fellows (akin to LDA, national money backing).

**Random issues:**

Public perception is king.

Slide 4

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