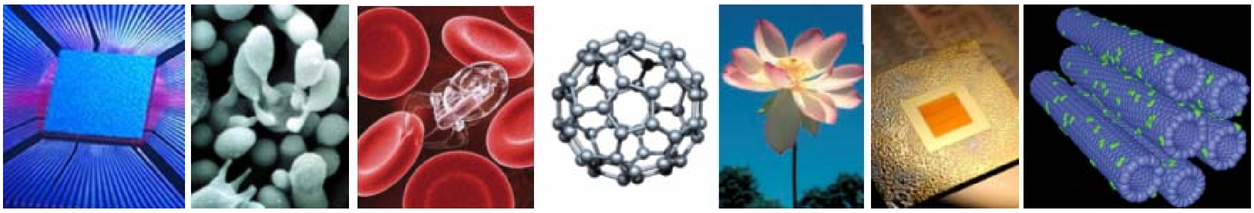
Nanotechnology



Enabling technologies for Australian innovative industries

11 March 2005

This paper was prepared by an independent working group for the Prime Minister's Science, Engineering and Innovation Council (PMSEIC). Its views are those of the group, not necessarily those of the Australian Government.

CONTENTS

Working group membership

Dr Deborah Rathjen, CEO and Managing Director, Bionomics Ltd (Chair)

Dr Leanna Read, Managing Director, TGR BioSciences Pty Ltd (Chair)

Dr Peter Binks, Director, Nanotechnology Victoria (Nanovic)

Professor Robert Clark, Professor of Experimental Physics, University of New South Wales and Director, Centre for Quantum Computer Technology (Federation Fellow)

Dr Bruce Cornell, Chief Scientist and Senior Vice President, AMBRI Pty Ltd

Professor Erol Harvey, Professor of Microtechnology, Swinburne University of Technology and Chairman/Managing Director, MiniFAB Pty Ltd

Mr Brian Innes, Business Development Manager, Advanced Nanotechnology Limited

Professor Chennupati Jagadish, Professor of Electronic Materials Engineering, Australian National University and Head, Australian Research Council Nanotechnology Network (Federation Fellow)

Professor Max Lu, Professor of Chemical Engineering, University of Queensland and Director, ARC Centre for Functional Nanomaterials & NanoQuest Pty Ltd (Federation Fellow)

Dr Terry Turney, Director, CSIRO Nanotechnology Centre

Terms of reference

The PMSEIC working group on nanotechnology will:

1. Outline the importance and potential applications of nanotechnology as an enabling technology to many industries.
2. Examine what nanotechnology has delivered to date. Particular consideration should be given to:
   - the uptake of nanotechnology by mainstream industries; and
   - differentiating between incremental and disruptive innovations.
3. Scope Australia's international competitiveness.
   - How internationally competitive is Australia in nanotechnology?
   - What policies and programs do key competitor nations have in place?
4. Identify major challenges and opportunities.
   - What is industry's preparedness for nanotechnology uptake?
   - What are the areas of potential community concern?
   - How do we build and capitalise on Australia's unique advantages?
   - What should be done in Australia over the next 5 years (2005–10) and the following 5 years (2010–15)?

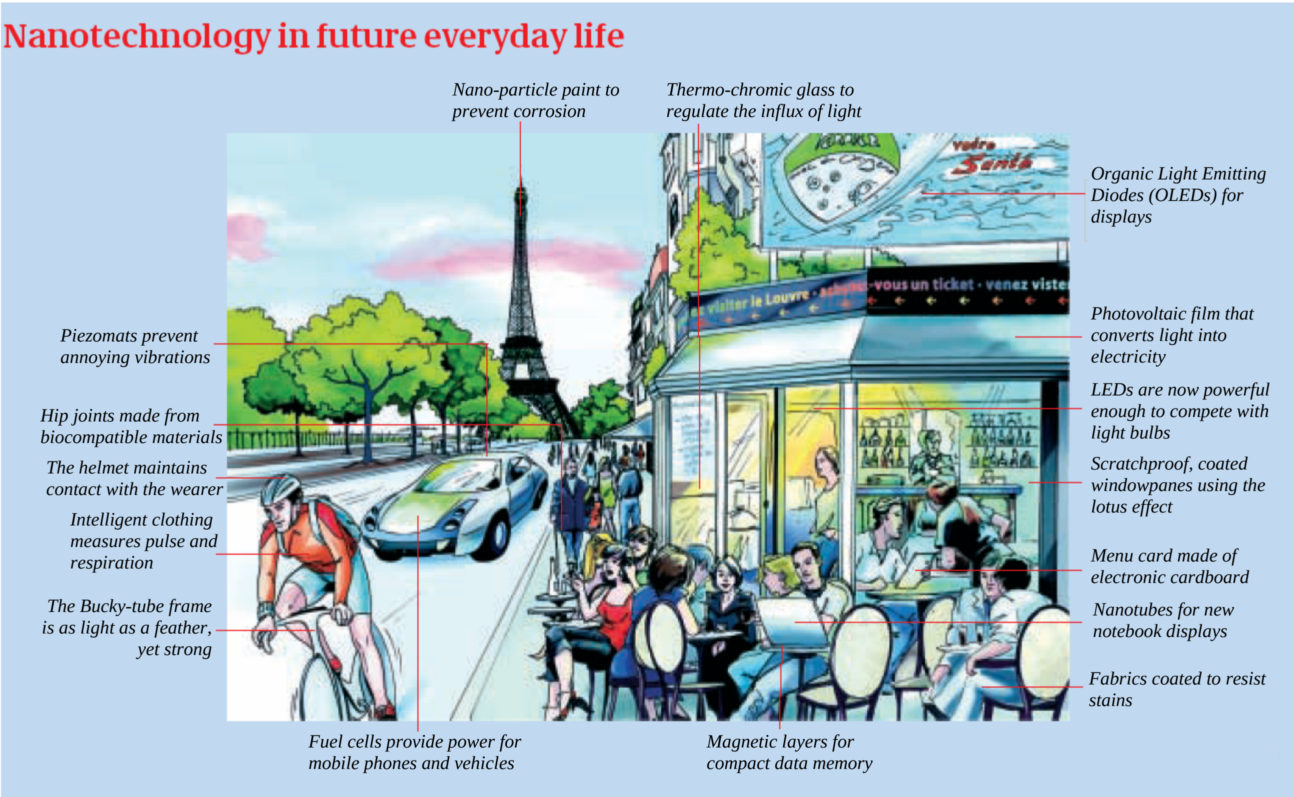
Executive summary, key findings and recommendations

Nanotechnology is engineering at the molecular (groups of atoms) level. It is the collective term for a range of technologies, techniques and processes that involve the manipulation of matter at the smallest scale (from 1 to 100 nanometres — 1/10,000th the thickness of a human hair).

At this very small scale, the properties of materials such as colour, magnetism and the ability to conduct electricity change in unexpected ways. This results in new, exciting and different characteristics that can generate a vast array of novel products.

Because nanotechnology is classified by the *size of the materials* being developed and used, the products of this engineering can have little in common with each other — for example fuel cells, fabrics or drug delivery devices. What brings them together is the natural convergence of all basic sciences (biology, physics and chemistry) at the molecular level.

Nanotechnology is not new. Nanoproducts are already in the marketplace, such as stain-resistant and wrinkle-free textiles. But because it transcends the conventional boundaries between physics, chemistry, biology, mathematics, information technology, and engineering, nanotechnology has the potential to transform the way we live. Some of the ways in which nanoproducts are predicted to impact on everyday life are illustrated in the cartoon below from the EU publication *Nanotechnology: Innovation for tomorrow's world*[1].



[1] European Commission *Nanotechnology Innovation for tomorrow's world* European Commission, Research DG, May 2004

The disruptive innovations that should arise from nanotechnology over the next decade could be as significant as electricity or the microchip. They could give rise to a whole new set of industries as well as transform current technologies in manufacturing, healthcare, electronics and communications. It has been estimated that the sales of products incorporating emerging nanotechnologies will rise from 0.1% of global manufacturing output in 2004 to 15% in 2014, totalling US$2.6 trillion. This would be as large as information and communication technologies combined and more than ten times larger than biotechnology revenues. Importantly, unlike information technology where, for example, consumers might buy a computer, nanotechnology consumers will not buy a 'nanotechnology product' but will buy a product developed or enhanced through nanotechnology.

It is very timely for PMSEIC to revisit the topic of nanotechnology because there has been an explosion in technological developments worldwide over the last 5 years, global investment has quadrupled (and now exceeds US$8 billion per year) and important practical applications of nanotechnology are emerging.

Examples of exciting applications of nanotechnology include:

- *Nanopowders* — the unusual properties of particles less than 100 nm allow a range of new and improved materials with a breadth of applications, such as plastics that behave like ceramics or metals; new catalysts for environmental remediation; improved food shelf-life and packaging; and novel drug delivery devices.
- *Carbon nanotubes* — graphite can be rolled into a cylinder with a diameter of about 1 nm. These strong but light 'carbon nanotubes' are being developed for a raft of uses, such as sensors, fuel cells, computers and televisions.
- *Nanomembrane filtration systems* — these have the potential to address one of the most pressing issues of the 21st Century — safe, clean, affordable water.
- *Molecular electronic 'cross bar latches'* — Hewlett-Packard believes that silicon computer chips will probably reach a technical dead end in about a decade, to be replaced by tiny nanodevices described as 'cross bar latches'.
- *Quantum dots* — these are small devices that contain a tiny droplet of free electrons — essentially artificial atoms. The potential applications are enormous, such as counterfeit-resistant inks, new bio-sensors, quantum electronics, photonics and the possibility of tamper-proof data transmission.
- *New technologies for clean and efficient energy generation*.

Developments of this nature will undoubtedly bring significant risks and rewards, as well as raise social and ethical issues that must be addressed in parallel with scientific advancement.

If just a fraction of its potential for social, economic and technological change is realised, then Australia cannot afford to ignore nanotechnology. Global developments in nanotechnology will certainly impact on many of Australia's most important traditional industry sectors, and will raise social and safety issues that must be addressed. Australia has a strong, but fragmented, research base and nanotechnology capability is growing across a number of industry sectors in Australia, including minerals, agribusiness, health and medical devices, and energy and environment. Australia also has the opportunity to be an important player in the emergence of entirely new industries.

The challenge for the next decade is to ensure that the full potential of this exciting technology can be harnessed, while ensuring that the social, ethical and safety issues are properly addressed.

Key findings

Australia's research base is strong and globally competitive in particular areas as evidenced by world leading technologies being developed for diagnostic devices, nanomaterials, quantum computing and energy storage. Our nanotechnology R&D is already making significant contributions to mainstream industry, and Australian industry will become increasingly reliant on nanotechnology solutions over the next 5-10 years.

The Australian nanotechnology effort is necessarily small by global standards, but even the largest countries will be faced with the prospect that nanotechnology will become more expensive, complex, multidisciplinary and dispersed globally. While these developments pose major problems for smaller players, all players will be seeking strategic alliances. Good research performers, such as Australia, should find plenty of opportunities by pursuing international collaboration.

To capitalise on the opportunities presented by nanotechnology, the challenge is to enhance the coordination of Australia's nanotechnology effort, concentrate resources and accelerate industry uptake.

Specific needs identified by the working group were:

1. The need for a national nanotechnology strategy coordinated across all levels of government, to inform the public debate on social, health and environmental issues, and to provide an appropriate regulatory framework.

2. Our ability to impact on technologies that will become important for industry on a 10 year timeframe and beyond will require long term support of Australian fundamental nanoscience research as this will underpin the disruptive innovations that have the capacity to transform current technologies and industries.

3. Nanotechnology initiatives in Australia are continuing to grow in number and resource commitments. If these are to achieve world-competitive outcomes, some consolidation and clustering of research effort is needed.

4. Even large countries are recognising the importance of international cooperation in a field as dynamic, expensive and multidisciplinary as nanotechnology. Australia cannot possibly remain at the cutting edge of the global nanotechnology revolution if its research is not highly integrated with international centres of excellence.

5. Mechanisms are needed to support and strengthen Australia's fledgling nanotechnology industries, and to enhance the awareness and uptake of nanotechnology in the broader mainstream industry sectors.

6. Because most Australian nanotechnology is currently driven by academic research, links between industry and the public sector research base need to be enhanced if Australia is to capture the full economic potential of this transforming technology.

7. Australia must ensure it has the full complement of infrastructure needed to underpin a globally competitive position in nanotechnology — characterisation tools, nanoscale science, molecular level computations and fabrication and processing technology. The National Collaborative Research Infrastructure Strategy (NCRIS) would appear to be an appropriate vehicle to address these infrastructure needs.

8. We must address emerging issues concerning community awareness and acceptance of nanotechnology, as well as the considerable ethical, social and safety implications.

9. The development of a comprehensive impact and risk analysis framework must be seen as a high priority. This framework must adopt a science-based risk identification, assessment and management process.

10. The development of a substantial Australian skills base in nanotechnology is of fundamental importance to our nanotechnology capability over the next decade.

Recommendations

The needs identified by the working group fall into two categories — those that require government coordination and those that are best addressed by the private sector.

Government is best positioned to implement measures that will ensure a national and coordinated approach on nanotechnology, appropriate representation of Australia's interests at international forums, well-informed public awareness activities and debate, and an appropriate regulatory framework.

The private sector needs to create a collective voice for the emerging nanotechnology industry and develop a range of initiatives to support and strengthen Australia's nanotechnology business community.

The situation Australian nanotechnology faces at this time is similar to that encountered by the biotechnology and ICT sectors 5-10 years ago — with the industry component characterised by small, under-capitalised emerging business enterprises, a growing academic research capability, which is showing signs of a collaborative approach, and several state government investment initiatives into nanotechnology. There is also commonality with biotechnology in terms of community concerns with public safety associated with new technologies.

The opportunity to create an ICT industry was not capitalised on in part due to the failure to generate a critical mass, and a lack of coordination of R&D effort in Australia. By contrast, the Australian Government addressed the biotechnology situation by the implementation in 2000 of an Australian National Biotechnology Strategy.

The working group sees merit in the commissioning of a national nanotechnology strategy. This strategy should take into account the need to coordinate across all levels of government, to inform the public debate on social, health and environmental issues, and to provide an appropriate regulatory framework that safeguards the health and safety of Australians.

Although there are differences between biotechnology and nanotechnology, such as the breadth of technologies and product applications, the process adopted for the formulation and implementation of the national biotechnology strategy may be useful in the context of the formulation and implementation of a national nanotechnology strategy.

The working group feels that this task cannot wait — Australia could risk being marginalised in a technology that has the potential to transform the way we live.

Recommendation 1

That the Australian Government examine the options for implementing a national nanotechnology strategy, with particular emphasis on the framework under which the objectives of a national nanotechnology strategy can be achieved.

This national nanotechnology strategy should provide a broadly based framework to ensure that Australia has:

- A national and coordinated approach on nanotechnology with the states/ territories/federal governments and industry, including an appropriate body to ensure such coordination
- Provision of high level advice to governments on nanotechnology issues, business development and R&D support, global trends, major infrastructure requirements, and development of Australian skills base
- Appropriate representation of Australia's interests at international forums
- Well-informed public awareness activities and debate on social, health and environmental issues
- An appropriate regulatory framework which safeguards the health and safety of Australians.

The advantages of the above coordinated approach would include:

- Responding to the need to coordinate what is currently a high quality but small, diverse and disparate national research effort in nanotechnology
- Building on the strategic lessons of the biotechnology initiative
- Providing a model which incorporates states/territories/federal government consultation framework
- Being able to respond to the wide range of cross-portfolio issues including regulation and public concerns regarding potential health and safety issues.

Recommendation 2

That an Australian nanotechnology business alliance be formed with government support whose role is to overcome the current fragmentation evident in the nanotechnology sectors, link business and researchers, and enhance industry application of nanotechnology.

An industry alliance/organisation of this kind would provide benefits such as:

- Fostering cross-sector collaboration and links
- Building confidence of the investment community
- Facilitating the adoption of regulatory frameworks
- Enhancing the uptake of nanotechnology solutions in mainstream industries

- Driving convergence of traditional disciplines that underpin disruptive innovations.

By analogy with biotechnology, 'AusNanotech' (or other appropriate name) would act as a non-governmental nanotechnology association and facilitator. It would serve to create a collective voice for the emerging nanotechnology industries and develop a range of initiatives to support and strengthen Australia's nanotechnology business community.

Specific issues to be addressed by the business alliance could include:

- Contribution to public policy by developing an industry-wide position on key issues related to the establishment, growth and competitiveness of Australian nanotechnology businesses and by providing advice to commonwealth, state and local governments on such issues
- Engaging in public debate concerning nanotechnologies and promoting Australian nanotechnology industries both in Australia and overseas
- Fostering industry-wide R&D on key common issues
- Establishment of nanotechnology industry hubs
- Identifying industry infrastructure needs
- Establishment of those enabling and platform nanotechnologies which are key to viability, competitiveness and diversification of the industry
- Educational and networking opportunities for nanobusiness people.

If the biotechnology model proves to be appropriate, there will be the opportunity to draw on the considerable experience, strategic planning and business systems of AusBiotech. Experience can also be drawn from other successful nanotechnology business alliances that have been established in the USA, Canada, Israel, European Union, Austria and Scandinavia. This should allow AusNanotech to achieve its goals in a much shorter time than the four years required for AusBiotech to reach its current position as the peak industry body.

The next National Nanotechnology Conference, due to be held in September 2005, would provide an ideal opportunity to begin establishing this body. Initial support will be required to build infrastructure and support the initial activities until AusNanotech is self-sustaining.

The government and non-government approaches proposed should interact in a productive way to maximise the benefits to Australia of its investments in nanotechnology research and support continued growth of the nanotechnology business sector including the uptake of nanotechnology enhanced products by Australian consumers.

1 Introduction

In preparing this report the PMSEIC nanotechnology working group invited submissions from government agencies and agencies and organisations involved in nanotechnology R&D including both small and large companies (see Appendix 1).

1.1 What is nanotechnology?

Nanotechnology is engineering at the molecular (groups of atoms) level. It is the collective term for a range of technologies, techniques and processes that involve the manipulation of matter at the smallest scale (from 1 to 100 nm[2]).

The classical laws of physics and chemistry do not readily apply at this very small scale for two reasons. Firstly, the electronic properties of very small particles can be very different from their larger cousins. Secondly, the ratio of surface area to volume becomes much higher, and since the surface atoms are generally most reactive, the properties of a material change in unexpected ways. For example, when silver is turned into very small particles, it takes on anti-microbial properties while gold particles become any colour you choose.

Nature provides plenty of examples of materials with properties at the nanoscale – such as the iridescence of butterfly wings, the sleekness of dolphin skin or the 'nanofur' that allows geckos to walk up vertical surfaces. This latter example is illustrated in Figure 1. The Gecko foot pad is covered with aggregates of hair formed from nanofibres which impart strong adhesive properties.

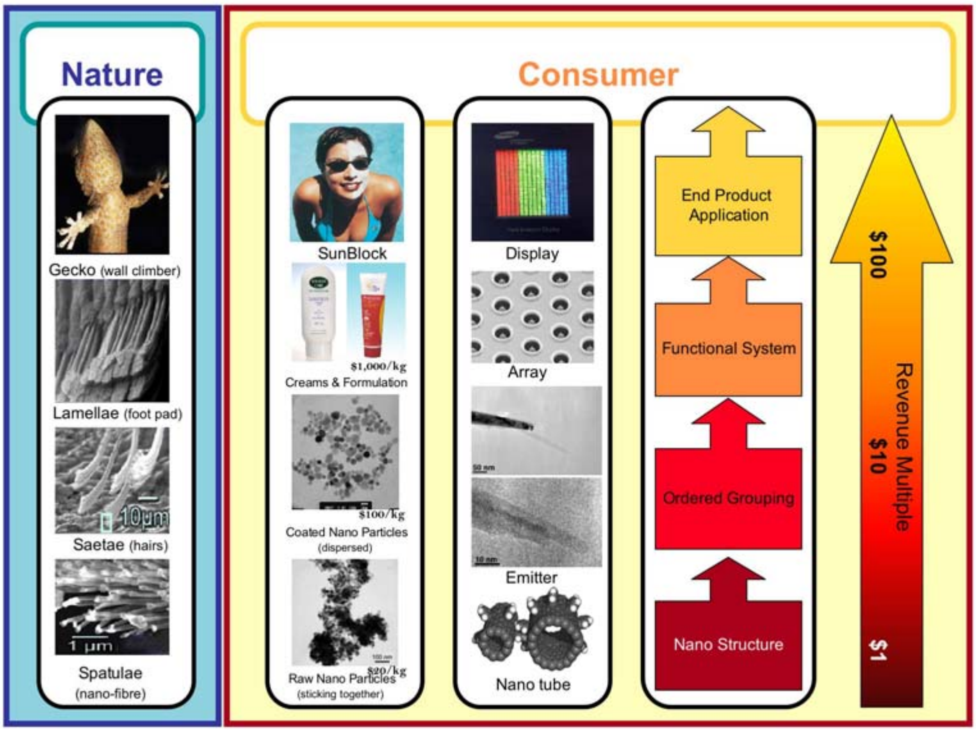


Figure 1. Examples of nanostructures in nature and nanotechnology

2 One nanometre (1 nm) is defined as one billionth of a metre (10^{-9} m). This is the diameter of several atoms, and on the scale of individual molecules. A human hair is approximately 80 000 nm wide, a red blood cell is 7000 nm wide, a DNA molecule is approximately 2 nm wide.

Nanotechnologists use similar principles to deliberately engineer at the nanoscale to create products that make use of these unusual properties. Starting with nanostructures, scientists rearrange them and then assemble functional systems that can be incorporated into products with unique properties. Figure 1 shows two examples. Firstly, the propensity for carbon to form tubes at the nanoscale can be used to generate arrays over micron sized conductors that illuminate flat panel displays for mobile phones, and secondly nanoparticles can be manipulated to create effective, fully transparent sunblock creams. These are but two of many examples of stronger, stickier, smoother and lighter products being developed.

1.2 Nanotechnology is a set of enabling technologies

Nanotechnology is not confined to one industry, or market. Rather, it is an enabling set of technologies that cross all industry sectors and scientific disciplines. Probably uniquely, it is classified by the *size of the materials* being developed and used, not by the processes being used or products being produced. Nanoscience is inherently multidisciplinary: it transcends the conventional boundaries between physics, chemistry, biology, mathematics, information technology, and engineering. This also means it can be hard to define – is the introduction of foreign genes or proteins into cells biotechnology or nanotechnology? And since genes have genetic memory, might this also be a form of information technology? The answer is probably ‘all of the above’. The important point is that the integration of these technologies and their manipulation at the molecular and sub-molecular level will over the next decade provide major advances across many existing industries and create whole new industries.

1.3 Why is there so much interest in nanotechnology?

Nanotechnology is not new – nanoproducts are already in the marketplace, such as stain-resistant and wrinkle-free textiles. Given its fuzzy definition, there is also an element of rebadging traditional products under the nanotechnology banner.

However, because nanotechnology is ubiquitous but also far-reaching, it has real potential to transform the way we live. There are very significant economic, social and environmental implications from this technology. To quote *The Economist* (January 2005): ‘Nanotechnology will indeed affect every industry through improvements to existing materials and products, as well as allowing the creation of entirely new materials’ [and] ‘produce important advances in areas such as electronics, energy and biomedicine’.

Investment in nanotechnology has more than quadrupled over the last four years, with expenditure now exceeding US$8 billion worldwide[3]. Global private investment will soon overtake government expenditure, indicating a maturing of the technology with practical applications becoming more evident.

The disruptive innovations that arise from nanotechnology over the next decade could be as significant as electricity or the microchip. They could give rise to a whole new set of industries as well as transform current technologies in manufacturing, healthcare, electronics and communications. It has been estimated that the sales of products incorporating emerging nanotechnologies will rise from 0.1% of global manufacturing output in 2004 to 15% in 2014,

3 *Small Wonders, A survey of nanotechnology*, The Economist, 1 January 2005.

totalling US$2.6 trillion[4]. This would be as large as information and communication technologies combined and more than ten times larger than biotechnology revenues. But unlike information technology where for example, consumers might buy a computer, nanotechnology consumers will not buy a 'nanotechnology product' but will buy a product developed or enhanced through nanotechnology.

Developments of this nature will undoubtedly bring significant risks and rewards, as well as raise social and ethical issues. For these reasons, the current level of interest surrounding nanotechnology would seem to be warranted.

1.4 Why is nanotechnology important to Australia?

Global developments in nanotechnology will certainly impact on many of Australia's most important traditional industry sectors, and will raise social and safety issues that must be addressed. Nanotechnology capability is growing across a number of industry sectors in Australia, including minerals, agribusiness, health and medical devices, and energy and environment. Even more significantly, Australia has the opportunity to be an important player in the emergence of entirely new industries.

We have also invested substantial research effort and funding in nanotechnology and will need to continue this if we are to retain a competitive position in this global and rapidly expanding opportunity.

Even if just a fraction of its potential for social, economic and technological change is realised, then Australia cannot afford to ignore nanotechnology.

1.5 Why another report on nanotechnology?

PMSEIC considered nanotechnology as an issue in 1999, as did its predecessor ASTEC (the Australian Science, Technology and Engineering Council) in 1994. In 1994, ASTEC reported that nanotechnology was a nascent technology, with industry developments and government awareness just beginning to emerge worldwide[5]. By 1999, PMSEIC recognised the need to promote this area of research and to map Australia's capabilities[6]. As a result, Australia's first nanotechnology conference was held (2001), and the first audit of nanotechnology capability was published (2003).

The explosion in technological developments worldwide over the last 5 years, as well as the realisation of practical applications of nanotechnology, mean that it is timely to revisit the topic. Also, there have been significant developments in the Australian context, as summarised in the following box. It is also timely to report on the social and ethical implications of this new technology. Now that the practical applications of nanotechnology are being realised, issues of safety and social impact are surfacing. Parallels are being drawn with genetically modified foods, leading to some calls for a moratorium on nanotechnology until the risks are better understood. On the other hand, the public at large has little understanding of nanotechnology.

---

4 Lux Research, *Sizing Nanotechnology's Value Chain*, New York, 2004. Note that this revenue will not be available solely to nanotechnology companies and that much of this revenue will be transferred from other, soon to be superseded, products.

5 *Small Things – Big Returns The Role of Nanotechnology in Australia's Future* ASTEC Occasional Paper No.26 , May, 1993.

6 PMSEIC *Nanotechnology: the Technology of the 21st Century* 1999. http://www.dest.gov.au/science/pmseic/documents/Nanotech.pdf (accessed 1 February 2005)

For all these reasons, it is important for PMSEIC to revisit the issue of nanotechnology to ask whether all the attention is justified, identify the key policy issues, and determine how Australia can position itself to extract maximum benefit from this promising technology. This task cannot wait – Australia could risk being marginalised in a technology that has the potential to transform the way we live.

Nanotechnology developments in the last 10 years (1994-2004)

Globally

- Overall investment in nanotechnology increased 10-fold during this decade, with similar growth in the number of patents filed in this field.
- Government annual spending on nanotechnology more than quadrupled between 2000 and 2004, from approximately US$1 to US$4.5 billion. Total spending in 2004 including government, companies and venture capital was US$8.6 billion.
- Major public sector R&D initiatives on nanotechnology were announced over the past 5 years in the USA, Japan, European Union, China, Korea, Taiwan and UK.
- Lux Research (USA) projects that internationally, private sector spending will exceed that of governments after 2004. Some 1500 companies have announced nanotechnology R&D plans, of which 80% were start-ups.
- Global sales of products derived from emerging nanotechnologies are estimated to escalate to over US$2 trillion per annum in the next ten years, with between 1 and 2 million new jobs generated.

In Australia

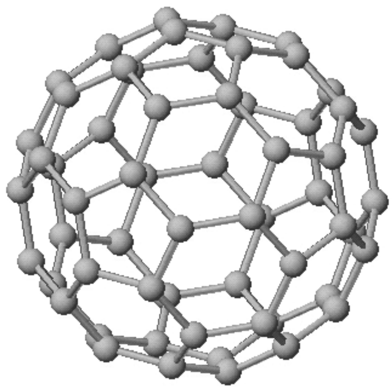
- The 1999 PMSEIC report noted Australia's lack of commercialisation infrastructure and suggested the establishment of a national tool box of nanotechnology facilities and a national strategy to coordinate and focus efforts.
- In 2001, the Australian Government announced the *Backing Australia's Ability* package providing A$3 billion in science and innovation funding until 2005-06. Nanotechnology research benefited from this influx of research funding.
- In late 2002, Australia identified nanotechnology as an example technology under its National Research Priority goals.
- In mid 2003, the Nanotechnology Victoria (Nanovic) consortium and the Australian Institute for Bioengineering and Nanotechnology (AIBN) were established.
- At a rough estimate, by 2003, governments and the private sector were investing up to A$100 million per annum in nanotechnology, with at least half from government sources.
- In May 2004, the Australian Government expanded *Backing Australia's Ability* funding to provide A$8.3 billion in science and innovation funding until 2010-11.
- In 2004, a benchmarking report undertaken by the Australian Academy of Science identified high quality research in this field, whilst noting Australia was not advancing as quickly as the rest of the world.
- By 2004, Australia had some 70 nanotechnology research groups and an ARC network.
- Over the decade, at least 40 new Australian nanotechnology companies were established, while a number of major companies have included nanotechnology in their strategic planning.

2 What's happening globally?

2.1 Brief history of nanotechnology

Nanoparticles of gold and silver have been found in Ming dynasty pottery and stained glass windows in medieval churches. However, the origins of nanotechnology did not occur until 1959, when Richard Feynman, US physicist and Nobel Prize winner, presented a talk to the American Physical Society annual meeting entitled *There's Plenty of Room at the Bottom*[7]. In his talk, Feynman presented ideas for creating nanoscale machines to manipulate, control and image matter at the atomic scale. In 1974, Norio Taniguchi introduced the term 'nanotechnology' to represent extra-high precision and ultra-fine dimensions, and also predicted improvements in integrated circuits, optoelectronic devices, mechanical devices and computer memory devices[8]. This is the so called 'top-down approach' of carving small things from large structures. In 1986, K. Eric Drexler in his book *Engines of Creation* discussed the future of nanotechnology, particularly the creation of larger objects from their atomic and molecular components, the so called 'bottom-up approach'[9]. He proposed ideas for 'molecular nanotechnology' which is the self assembly of molecules into an ordered and functional structure.

The invention of the scanning tunneling microscope by Gerd Binnig and Heinrich Rohrer in 1981 (IBM Zurich Laboratories), provided the real breakthrough and the opportunity to manipulate and image structures at the nanoscale. Subsequently, the atomic force microscope was invented in 1986, allowing imaging of structures at the atomic scale. Another major breakthrough in the field of nanotechnology occurred in 1985 when Harry Kroto, Robert Curl and Richard Smalley invented a new form of carbon called fullerenes ('buckyballs'), a single molecule of 60 carbon atoms arranged in the shape of a soccer ball. This led to a Nobel Prize in Chemistry in 1996.



C60 image from the Sussex Fullerene Research Centre (www.sussex.ac.uk)

Since that time, nanotechnology has evolved into one of the most promising fields of science, with multi-billion dollar investments from the public and private sectors and the potential to create multi-trillion dollar industries in the coming decade.

2.2 Unifying themes of nanotechnology

Because nanotechnology is classified by the *size of the materials* being developed and used, the products of this engineering can have little in common with each other – for example fuel cells, fabrics or drug delivery devices. What brings them together is the natural convergence of all basic sciences (biology, physics, and chemistry) at the molecular level. At this level, these diverse fields are unified by the following common themes:

7 Richard Feynman *There's Plenty of Room at the Bottom. An Invitation to Enter a New Field of Science*, lecture, annual meeting of the American Physical Society, California Institute if Technology, December 29, 1959. http://www.zyvex.com/nanotech/feynman.html (accessed 15 February 2005)

8 N. Taniguchi, *On the Basic Concept of 'NanoTechnology',* Proc. Intl. Conf. Prod. Eng. Tokyo, Part II, Japan Society of Precision Engineering, 1974.

9 K.E. Drexler, *Engines of Creation*, Anchor Press, New York, 1986.

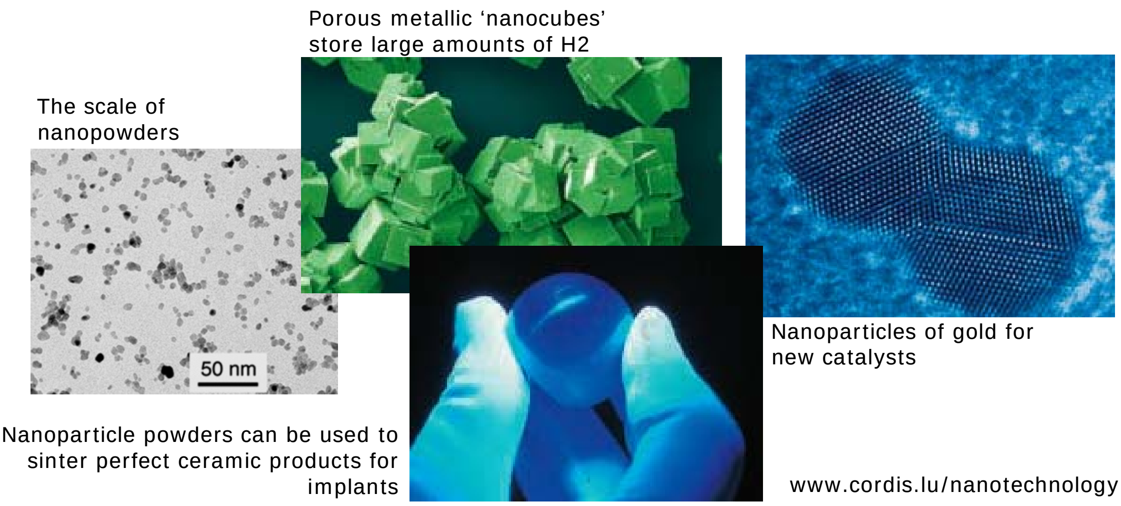
1. *Characterisation tools* — to be able to examine and see the nanostructures or the building blocks of nanomaterials, characterisation tools such as X-ray diffraction, Synchrotron, Scanning and Transmission Electron Microscopy, Scanning Tunneling and Atomic Force Microscopy are powerful tools across disciplines.
2. *Nanoscale science* — because the properties of materials change in unexpected ways at the nanoscale, the science of understanding the behavior of molecules at this scale is critical to the rational design and control of nanostructures for all product applications.
3. *Molecular level computations* — computation technologies such as quantum mechanical calculations, molecular simulations and statistical mechanics are essential to the understanding of all nanoscale phenomena and molecular interactions.
4. *Fabrication and processing technology* — many nanoparticles, powders and suspensions can be directly applied in paints, cosmetics, and therapeutics. However, other nanomaterials must be assembled and fabricated into components and devices. In addition, processing techniques such as sol-gel, chemical vapor deposition, hydrothermal treatment, and milling are common techniques.

2.3 Examples of nanotechnology

Nanopowders – building blocks of nanomaterials

Nanopowders contain particles less than 100 nm in size — 1/10,000th the thickness of a human hair. The physical, chemical and biological properties of such small particles allow industry to incorporate enhanced functionalities into products.

Some of the unique properties of interest to industry are enhanced transparency from particles being smaller than the wavelength of visible light, and high surface areas for enhanced performance in surface area-driven reactions such as catalysts and drug solubilisation.



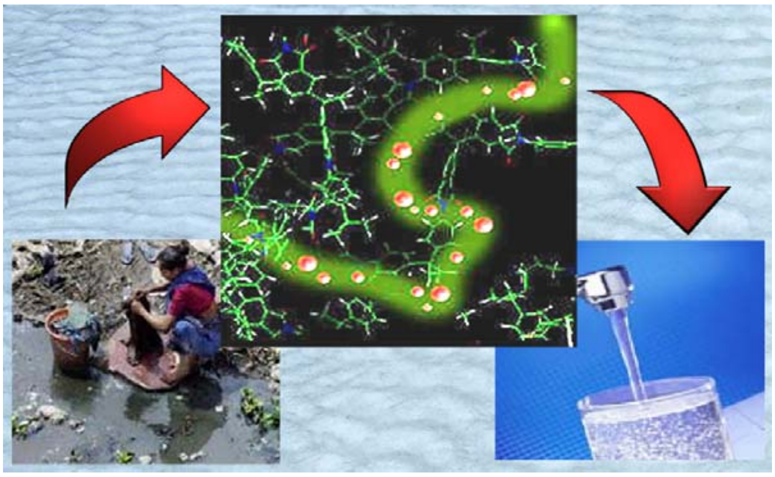
These unique properties give rise to a range of new and improved materials with a breadth of applications. For example, nanotechnology allows plastics to retain transparency while also taking on characteristics such as resistance to abrasion, conductivity or UV protection found in ceramics or metals. New medical nanomaterials are being developed, such as synthetic bone and bone cement, as well as drugs with improved solubility to allow lower dosing, more efficient drug delivery and fewer adverse side effects.

The high surface areas of nanoparticles are being exploited by industry in catalysts that improve chemical reactions in applications such as cleaning up car exhausts and potentially to remove toxins from the environment. For example, petroleum and chemical processing companies are using nanostructured catalysts to remove pollutants — $30 billion industry in 1999 with the potential of $100 billion per year by 2015. Improved catalysts illustrate that improvements to existing technology can open up whole new markets — nanostructured catalysts look likely to be a critical component in finally making fuel cells a reality, which could transform our power generation and distribution industry.

Membranes

Nanotechnology can address one of the most pressing issues of the 21st Century — safe, clean and affordable water. There are 1.3 billion people without access to safe drinking water and indications are that global consumption of water will likely double in the next 20 years. Fresh water supplies are already limiting the growth of our cities — Australian cities such as Sydney and Perth are considering waste water reuse schemes to augment their water supplies, London is investing ₤200 million in desalination and Singapore recycles wastewater. Further technology development is required to make this cost effective and allow it to become a more mainstream water supply option.

Nanomembrane filtration devices that 'clean' polluted water, sifting out bacteria, viruses, heavy metals and organic material, are being explored by research teams in the US, Israel and Australia (at the UNESCO Centre for Membrane Science and Technology at the University of New South Wales and a consortium of CSIRO Divisions). The key to lowering the energy demand and improving throughput for desalination is in understanding how to selectively separate small molecules, and package these technologies for exploitation. Separation of molecules occurs efficiently in nature through membranes, such as the ion channels that remove salt from blood and the respiratory membranes that transport oxygen and carbon dioxide. In order to reduce the energy requirement for this process, nature provides large surface areas for the transport of molecules. A parallel approach is being developed by nanotechnologists for the production of nanoarchitectures for cost-effective filtration systems in large-scale water purification.

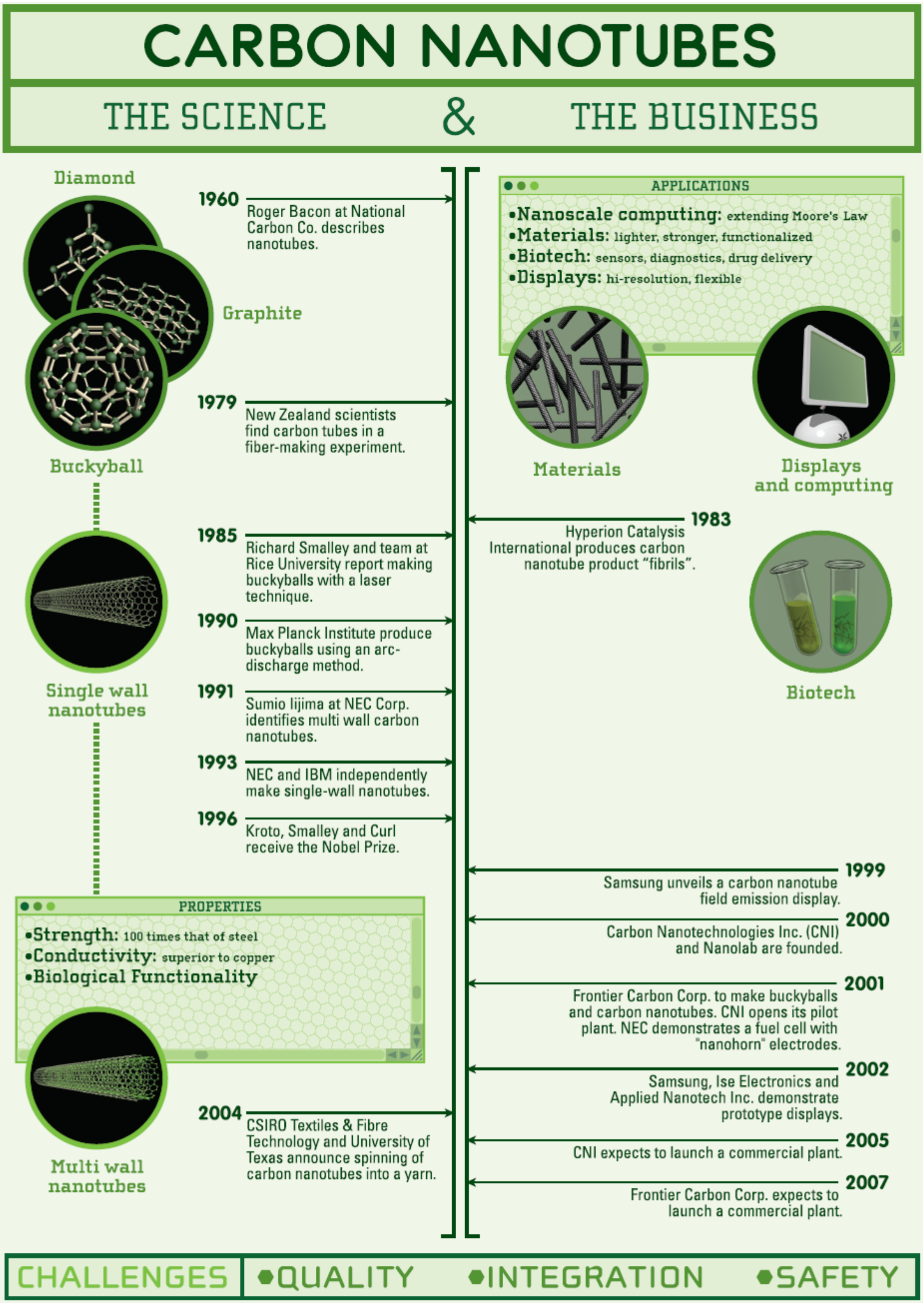


Clean, safe water passes through microstructured membranes.

By bringing science, business and government together on this issue, it should be feasible to find nanotechnology solutions to a global problem and transform a US$400-billion-a-year water-management industry.

Carbon nanotubes

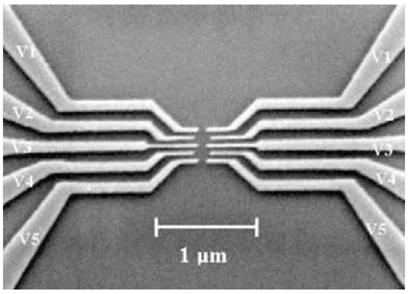
The discovery that graphite can be rolled into a cylinder with a diameter of about one nanometre already has far-reaching consequences. These strong but light 'carbon nanotubes' are being developed for a raft of uses, such as sensors, fuel cells, computers and televisions. The applications of nanotubes are set to expand even further now that scientists have found that other materials besides carbon can form nanotubes. The historical development of the science and the business of nanotubes is illustrated in the following chart.



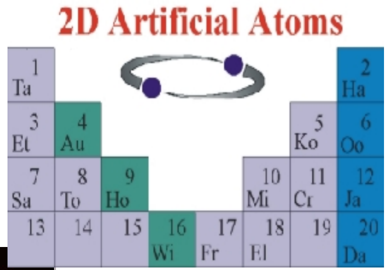
Quantum dots and artificial atoms

Quantum dots are small devices that contain a tiny droplet of free electrons. They are fabricated in semiconductor materials and have typical dimensions between nanometres to a few microns (10^{-6}m). A quantum dot can have anything from a single electron to a collection of several thousands. The physics of quantum dots show many parallels with the behaviour of naturally occurring atoms, but unlike their natural counterparts, quantum dots can be easily connected to electrodes and are therefore excellent tools to study atomic-like properties.

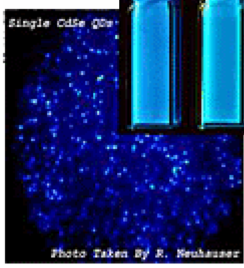
The capability to make artificial atoms is revolutionary. The potential applications are enormous such as counterfeit-resistant inks, new biosensors, quantum electronics, photonics and the possibility of tamper-proof data transmission. The technology also highlights the important regulatory and safety issues that must be addressed before widespread application of such disruptive technologies (see section 2.5).



Quantum dots can be made using electron beam lithography to create metal lines that are like wires only about 50 nanometers wide. The quantum dots (center of the image) are puddles of about 20-40 electrons.



Quantum dots are 2D analogies for real atoms. But since they have much larger dimensions they are suitable for experiments that can not be carried out in atomic physics.

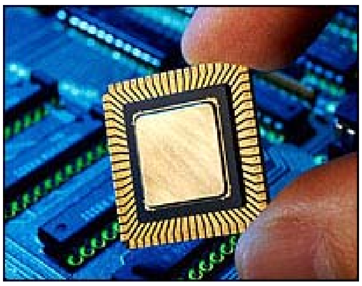


Unlike traditional liquid crystal displays, which must be lit from behind to work, quantum dots generate their own light.

Molecular electronics — cross bar latches to replace silicon chips

Hewlett-Packard — one of the world's biggest computer companies — declared on 1 February 2005 that it is on the verge of a revolution in computer chip technology[10]. They believe that silicon computer chips will have reached a technical dead end in about a decade, to be replaced by tiny nanotechnology devices described as ‘cross bar latches’. These molecular-scale alternatives to the transistor should dramatically improve the performance of computers because they are much smaller — only 2 or 3 nm in size compared with 90 nm for transistors — and they can store memory for much longer periods.

The new device consists of a wire that is crossed by two other wires. The resulting junctions serve as switches that are only a few atoms across and can be programmed by a repeatable set of electrical pulses.



http://news.bbc.co.uk

10 www.hp.com/hpinfo/newsroom/press/2005/050201a.html

New technologies for clean and efficient energy generation

The increased need for more energy will require enormous growth in energy generation capacity, more secure and diversified energy sources, and a successful strategy to tame greenhouse gas emissions. All the elementary steps of energy conversion take place on the nanoscale. Thus, the development of new nanoscale materials, as well as the methods to characterise, manipulate, and assemble them, create an entirely new paradigm for developing revolutionary energy technologies. A recent workshop led by the US Department of Energy[11] identified the following areas in which nanoscience is expected to have the greatest impact:

- Scalable methods to split water with sunlight for hydrogen production
- Highly selective catalysts for clean and energy-efficient manufacturing
- Harvesting of solar energy with 20 % power efficiency and 100 times lower cost
- Solid-state lighting at 50 % of the present power consumption
- Super-strong, light-weight materials to improve efficiency of cars, airplanes, etc
- Reversible hydrogen storage materials operating at ambient temperatures
- Power transmission lines capable of 1 gigawatt transmission
- Low-cost fuel cells, batteries, and supercapacitors built from nanostructured materials
- Materials synthesis and energy harvesting based on the efficient and selective mechanisms of biology.

The following table illustrates the range of innovations that are under development for clean energy and environmental applications, which incorporate nanotechnology.

	Radical innovation	Incremental innovation
Assembled products	- Fuel cells - Hydrogen storage systems - Molecular sieves for H_2 purification - Nano air and water purifiers	- Hybrid-electric vehicles - High performance batteries - Hydrogen sensors
Non-assembled products	- Nanopowders for hydrogen storage - Photocatalysts and nanocoatings - CO_2 separation and sequestration	- Catalysts for low-S fuel production - Steam reforming of natural gas to produce hydrogen - Coal to hydrogen conversion

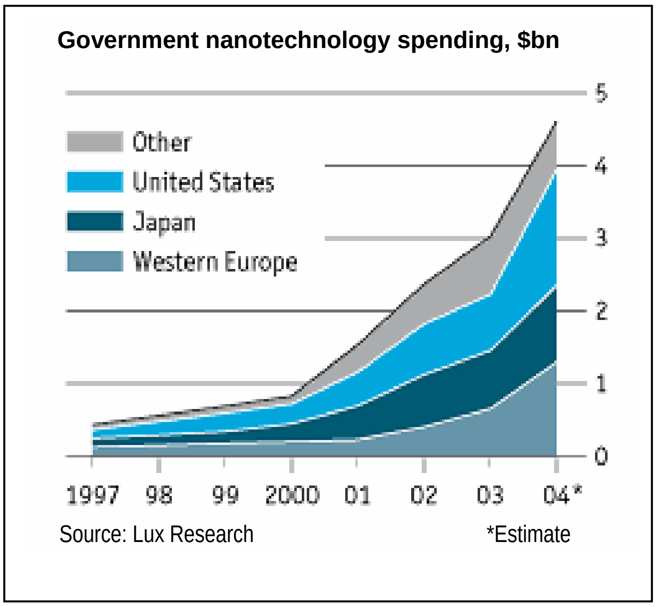
2.4 Growth in world investment in nanotechnology

The first half of this decade has seen an escalating interest in nanotechnology. Governments have led the wave of investment to date, with global government spending jumping from under US$1 billion in 2000 to over $4 billion in 2004[12]. Individual governments, including those of the USA, Japan, China, Taiwan, Israel, the United Kingdom and Germany, as well as the European Union, have announced substantial nanotechnology initiatives over the past five years. The USA in particular has made nanotechnology one of the largest funded science initiatives in its history, and its investment has overtaken Japan's. The US National

11 *Nanoscience research for energy needs*, Report of the March 2004 National Nanotechnology Initiative Grand Challenge Workshop, Arlington, VA, USA.

12 Lux Research, *Sizing Nanotechnology's Value Chain*, New York, 2004.

Nanotechnology Initiative was instigated in 2000, increasing annual funding to over US$960 million in 2004[13]. A *21st Century Nanotechnology R&D Act* (2004) provides an additional US$3.7 billion over the period 2005-2008. Nanotechnology is also one of the main science priority areas for Asia Pacific governments. Total spending for Asia Pacific countries has exceeded US$1billion for the past 2 years and will continue to increase[14].



A considerable portion of government investment, such as through the United Kingdom's Micro and Nanotechnology Manufacturing Initiative[15], is being directed towards the infrastructure needs of nanotechnology. This reflects the unique demands of measurements at the nanometre scale (nanometrology), as well as the challenges inherent in prototyping products and processes which cut across sectors and expertise in many research fields. Nanometrology is recognised as a key issue by national measurement institutes worldwide because it underpins the ability to attract international investment and partnerships. It also helps eliminate technical barriers to trade and underpins regulatory frameworks[16].

This, combined with the intensely multidisciplinary nature of nanotechnology itself, highlights the importance of collaboration on a global scale. Even the largest countries and multinational companies will be faced with the prospect that research efforts in nanotechnology will become more expensive, complex, multidisciplinary and dispersed globally. While these developments pose major problems for smaller players, all players will be seeking strategic alliances, and good research performers, such as Australia, should find plenty of opportunities by pursuing international collaboration.

Private sector investment is more difficult to assess than the public sector spend. According to Lux Research, industry commitment to nanotechnology was estimated at US$3.8 billion in 2004, taking the combined government and industry funding to over US$8 billion. Industry is now poised to overtake government expenditure for the first time. The global industry sector includes about 1500 companies. About 80% of these companies are start-ups, but the vast majority of expenditure comes from in-house efforts by major firms, with IBM, Intel, Hewlett-Packard, DuPont, Dow, Lucent, Eastman Kodak and 3M prominent among USA firms; and Sony, NEC, Matsushita, Mitsubishi, Mitsui, Hitachi leading the Japanese effort.

Venture capital firms currently invest a modest amount in nanotechnology enterprises, representing less than 2% of their investments. The total funding commitment by US venture capital firms was US$325 million in 2003[17].

---

13 http://www.nano.gov/

14 Summary of *Nanotechnology in Asia Pacific Report 2004*, http://www.researchandmarkets.com/reports/c11879/

15 http://www.dti.gov.uk/nanotechnology.

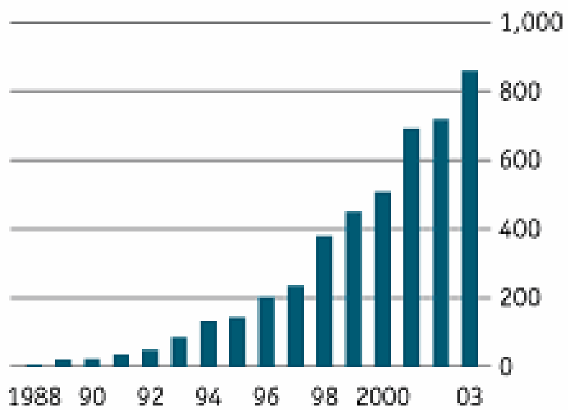
16 National Measurement Institute submission to the working group, November 2004.

This expected shift in balance of nanotechnology expenditure from the public to private sectors reflects a greater focus on applications of technology rather than development of basic science.

Not surprisingly, this has been accompanied by a growth of nanotechnology patents. By mid-2004 there were of the order of 20,000 patents and patent applications in the field of nanotechnology*18* with areas of greatest activity being:

- Nanoparticles
- Carbon nanotubes — methods of production or purification
- Carbon nanotubes — applications in electrodes
- Nano-based biological and chemical detection
- Nano-based drug delivery methods.

Selected nanotechnology patents*, United States



*Patents relating to the Atomic Force Microscope, quantum dot or dendrimer

Source: Lux Research

The top 10 worldwide nanotechnology patent assignees by 2004 were as follows:

Rank	Assignee	Patents
1	L'Oreal	266
2	International Business Machines (IBM)	125
3	Regents of the University of California	107
4	Eastman Kodak Company	84
5	Massachusetts Institute of Technology (MIT)	79
6	Henkel Kommanditgesellschaft	76
7	Japan Science and Technology Corporation	76
8	BASF Aktiengesellschaft	66
9	Allied Signal Inc.	65
10	Micron Technology, Inc.	62

It is clear from this brief overview that the promise of nanotechnology has excited considerable global interest and investment. Although future estimates of the outcomes of this investment are varied, Lux Research (USA) has estimated that the total market impact of nanotechnology on worldwide goods and services could exceed US$2 trillion by 2015[19]. Furthermore, between 800,000 and 2 million new jobs may be generated over this period.

2.5 Social, ethical and safety concerns

The introduction of any new technology attracts debate about potential social, environmental and health impacts - nanotechnology is no different. While some of the initial concerns raised about nanotechnology (such as US nanotechnology guru Eric Drexler's prediction of self-replicating nanomachines or 'nanobots', or the 'grey goo taking over the world' scenario) can

17 Lux Research, *The Nanotech Report*, US, 2004.

18 Micro and Nanotechnology Commercialization Education Foundation, Roadmap 2nd Edition, 2004.

19 Lux Research, *The Nanotech Report*, US, 2004.

be seen as speculative futuristic hypotheses[20], it is valid to question whether existing regulatory frameworks are appropriate to protect humans and the environment from potential hazards. A relatively small number of groups such as Canada's ETC Group have campaigned consistently against the introduction of nanotechnology[21]. Greenpeace, while recognising the potential benefits of nanotechnology, has urged caution on environmental, occupational health and safety grounds[22]. The working group considers that the development of a comprehensive impact and risk analysis framework must be seen as a high priority. This framework must adopt a science-based risk identification, assessment and management process.

Health and environmental impacts

A UK report released in 2004 by the Royal Society and the Royal Academy of Engineering concluded that many applications of nanotechnologies pose no new health or safety risks[23]. However, some nanoparticles — those which are freely mobile and not incorporated into a material — may have the potential for negative health and environmental impacts by virtue of their size or particular chemical properties[24,25]. The UK report therefore recommended that in the specific case of free nanoparticles and free nanotubes, existing regulatory frameworks need to be modified.

Relatively little research has been published on the human or eco-toxicology of man-made nanoparticles. In contrast, nanoparticles from natural sources are everywhere in the environment and there are well-established studies on other man-made, small airborne particles, such as mineral dusts and carbon soot. It is reasonable to assume that at least some manufactured nanoparticles may be more toxic per unit of mass than the bulk material. The UK report recommended that until more is known about the environmental impacts of nanoparticles and nanotubes, release into the environment should be avoided[26].

There may also be health risks from the medical application of nanoparticles, for example to enhance drug delivery. The existing regulatory agencies such as the US Food and Drug Administration and Australia's Therapeutic Goods Administration (TGA) and the National Industrial Chemicals Notification and Assessment Scheme (NICNAS) would be the appropriate vehicles to address and regulate such risks[27].

Social and ethical issues arising from nanotechnology–based products

As with any new technology, control over its use and distribution of benefits, rather than the technology itself, will determine the social impact of nanotechnologies rather than the technology itself. Nanotechnology does not operate independently of other technological developments (ICT, medicine, materials, energy etc), so that incremental advances made in nanotechnology may have major influences in other areas. It is difficult to predict the social

---

20 *Small wonders, A survey of nanotechnology*, The Economist, 1 January 2005, p.4

21 Action Group on Erosion, Technology and Concentration, *The Little Big Down: A Small Introduction to Nano-Scale Technologies*, Canada, June 2004, http://www.etcgroup.org/article.asp?newsid=471

22 Greenpeace, *Future Technologies, Today's choices – Nanotechnology, Artificial Intelligence and Robotics: A technical, political and institutional map of emerging technologies,* UK, 2003, http://www.greenpeace.org.uk/MultimediaFiles/Live/FullReport/5886.pdf.

23 UK Royal Society and the Royal Academy of Engineering, *Nanoscience and nanotechnologies: opportunities and uncertainties*, p.79-84.

24 UK Royal Society and the Royal Academy of Engineering, *Nanoscience and nanotechnologies: opportunities and uncertainties*, p. 35-50.

25 Jim Giles, *Nanotechnology: What is there to fear from something so small?*, Nature, Vol 426, 2004, p.750.

26 UK Royal Society and the Royal Academy of Engineering, *Nanoscience and nanotechnologies: opportunities and uncertainties*, p.50.

27 Submissions to the working group from Therapeutic Goods Administration (TGA), and NICNAS and NOHSC, November 2004.

and ethical implications of this convergence of various technologies, which are likely to hold a range of positive and possibly negative outcomes. It is also difficult to envisage the social impacts of what will be commercial decisions about use the of nanotechnology and business decisions about how products are marketed. The working group believes social issues need to focus on enabling community debate and choice, the economic impact of specific applications, inappropriate use of technology, equity and legal and regulatory frameworks.

Some specific examples of potential social and ethical impacts are as follows:

	Potential Positives	**Potential Negatives**
Developing world applications	Clean water, environmental remediation, cheaper medicines	A 'nanodivide' between rich and poor nations
Surveillance and data gathering	Improved business and service delivery	Compromised privacy
Defence	Better early warning of threats, defence capabilities	Personal and national security threats
Biotechnology	Improved drug delivery and disease treatment	Health risks, too invasive

These few examples illustrate the substantial social and economic benefit that nanotechnology should bring, but also the potential negative outcomes across society and to both developed and developing nations.

Although many of these concerns are still hypothetical, technical innovations tend to develop faster than all the stakeholders can keep up with. For these reasons, international policy formulation and public education on nanotechnology must be given high priority. For this reason, the US National Nanotechnology Initiative included funding for research on ethical, social and legal aspects of nanotechnology[28]. To consider these and related issues, the USA held an international, mostly governmental, conference in 2004 on responsible research in nanotechnology, which agreed to set up a 'Preparatory Group', of which Australia is a member[29]. The group is tasked to explore possible actions, mechanisms, timing, institutional frameworks and principles for an international dialogue and cooperation to occur on this in established international forums including the OECD's Global Science Forum. Australia also participates in other relevant forums such as the OECD Joint Meeting of the Chemicals Committee and the Working Party on Chemicals, Pesticides and Biotechnology; and the International Program on Chemical Safety[30].

Consideration of how to best build public awareness has already begun. In Europe in particular, there has been recognition of the need to avoid repetition of past mistakes associated with public engagement on the issue of genetically-modified foods. A key point taken up by independent groups such as DEMOS in the United Kingdom[31] and by

28 Dr John Marburger , Addresss, Workshop on Societal Applications of Nanoscience and Nanotechnology, National Science Foundation, Arlington Virginia, US, 3 December 2003.

29 Meridian Institute Report, 2004 – Australia informally represented by Professor Michael Barber, CEO CSIRO Science Planning.

30 National Chemical Notification and Assessment Scheme and the Office of National Occupational Health and Safety Commission, joint submission to the working group, November, 2004.

31 J Wilsdon & R Willis, *See-through Science: Why public engagement needs to move upstream*, DEMOS, London UK, 2004, pp. 57-59.

government agencies such as the Irish Council for Science, Technology and Innovation[32], is the need to establish public forums. It is unrealistic however to expect the general public to keep abreast of the expanding wave of innovation in nanotechnology, and public views will rely heavily on information conveyed by the scientific community and the media. For their part, the scientific community needs to be mindful that the challenges they perceive may not match those perceived by the wider community[33] and that narrow utilitarian approaches may not deliver an acceptable outcome to the public[34].

2.6 Conclusions on the global nanotechnology scene

No one could have predicted that the invention of the scanning tunneling microscope in 1981 would launch a revolutionary new technology that could be as significant as electricity or the microchip, transform whole industry sectors and generate product sales exceeding US$2 trillion by 2015. Like any other disruptive technology, nanotechnology offers both risks and rewards. The global developments in this field offer important lessons for Australia, notably:

- Global developments in nanotechnology will certainly impact on many of Australia's most important traditional industry sectors
- Nanotechnology has real potential to transform the way we live
- The potential social and ethical impacts of nano-derived products are considerable
- Collaboration on a global scale will be essential to realise the full potential of this multidisciplinary science
- In view of the massive global investment in nanotechnology, Australia will need to invest strategically to ensure we can maintain a competitive position.

The challenge for Australia, and indeed globally, over the next decade is to ensure that the full potential of this exciting technology can be harnessed, while ensuring that the social, ethical and safety issues are properly addressed.

32 Irish Council for Science, Technology and Innovation (NCSTI), NCSTI Statement on Nanotechnology,Ireland, 2004, pp. 70-72.

33 Dr John Marburger, Address, Workshop on Societal Applications of Nanoscience and Nanotechnology. National Science Foundation, Arlington Virginia, USA, 3 December 2003.

34 Dr Simon Longstaff, St James Ethics Centre, *Vision 2020: Nanotechnology and society in the year 2020* Nanotechnology Seminar, University of Western Sydney,24 November 2040 (proceedings as yet unpublished).

3 Australian nanotechnology

Chapter 1 outlined the reasons Australia cannot afford to ignore nanotechnology and chapter 2 placed nanotechnology in the global context. So where is Australia positioned by international comparisons? This section maps Australia's capabilities in nanotechnology and identifies the key challenges and opportunities for Australia to participate in the global nanotechnology revolution.

3.1 Public sector nanotechnology research

Research capability

Australia's nanotechnology research base is substantial, although small by global standards. Unlike a number of other advanced nations — the USA, the EU and the Asian group of Taiwan, Japan, South Korea and China — most Australian nanotechnology is still driven by academic research. Australia has world-class capability in the area of nanomaterials, with applications across the agriculture, energy, mining, environment, transport, healthcare and information technology sectors. Similarly, Australia has developed critical mass and expertise in both quantum-based nanotechnology and in electronics/photonics, with application to the information and communications sectors as well as many other industries.

A 2004 benchmarking report commissioned by the Australian Research Council and carried out by the Australian Academy of Science (AAS)[35] provides the most recent study of Australia's nanotechnology research base. The study highlighted the high quality of work produced by Australia's nanotechnology researchers, while noting that Australia is not advancing its capabilities as quickly as the rest of the world and is growing from a low base. Australia produced 1.41% of the world's nanotechnology publications from 1980 to 2003 and 1.49% between 1998 and 2003. This is a lower percentage for Australian science as a whole (2.8% since 1997). In terms of patents, Australia ranks 7th in the world (excluding USA) in the filing of US patents.

The Australian research effort is spread across the areas of nanobiotechnology and environmental applications, nanomaterials and nanoelectronics/photonics. Publications in each of these subfields have increased steadily since 1990, with nanobiotechnology the most highly cited (with 13.0 average citations per paper), followed by nanomaterials (with 11.0) and nanoelectronic/photonics (with 9.3).

The AAS 2004 benchmarking report also found extensive collaboration by Australian nanotechnology researchers with Europe and the US, and to a lesser extent with Asia. However, this would appear to largely reflect collaborations by individual research groups, rather than major strategically driven initiatives.

Australia's nanotechnology research institutions and funding

Nanotechnology is a major focus of research in some 70 Australian research groups located in CSIRO, DSTO and ANSTO, as well as a number of Australian universities. The following table summarises the relevant public sector networks, centres and institutions.

---

35 Warris, C. February 2004, *Nanotechnology Benchmarking Project*, Australian Academy of Science. Available online at: www.science.org.au/policy/nanotech.htm

Public sector networks, centres and institutions in nanoresearch

NETWORK	DESCRIPTION
Australian Research Council Nanotechnology Network (ARCNN)	This ARC research network established in 2004 brings together some 70 participant research groups working in nanotechnology and related areas in Australia. www.ausnano.net
Australian National Nanotechnology Network (ANNN)	The ANNN, brings together wider networks through representatives of the ARC, Academies, CSIRO, universities, State and Commonwealth governments, industry associations, investors and civic groups to facilitate technology diffusion.
CSIRO NanoScience Network	This Network reflects CSIRO's multidisciplinary approach to nanotechnology, and combines diverse strengths and expertise across CSIRO research divisions. www.nano.csiro.au
Nanotechnology in Australia	Australia's nanotechnology website portal, managed by DITR, provides a listing of research activities. www.nanotechnology.gov.au
OzNano2Life	Australian nanobiotech network, providing a portal to European nanotech institutes, in particular Nano2Life. www.nano.uts.edu.au
CENTRES	**DESCRIPTION**
ARC Centre of Excellence for Functional Nanomaterials	Nanomaterial applications for clean energy, environmental, and health care industries. www.arccfn.org.au
ARC Centre of Excellence for NanoElectromaterials	Creation of new nanostructured electrode materials. www.uow.edu.au/science /research/nsem/
ARC Centre of Excellence for Quantum Computer Technology	Single atom nanoelectronics and single photon nanophotonics applied to the construction of silicon solid state and linear optics quantum computing prototypes. www.qcaustralia.org/
ARC Centre of Excellence for Quantum-Atom Optics	Quantum-based nanotechnology applied to information and communications technologies. www.acqao.org/
Ian Wark Research Institute – ARC Special Res. Centre	Nanomaterials applied to energy and mining applications.
CRC for Advanced Composite Structures	Structural nanomaterials for aerospace, marine and general composites. www.crc-acs.com.au
Cooperative Research Centre for Microtechnology	Microtechnology, deployed in structures and devices. www.microtechnologycrc.com/
Bandwidth Foundry - MNRF	MNRF providing prototyping foundry services for manufacturing of photonic integrated circuits. www.bwfoundry.com
Nanostructural Analysis Network Organisation (NANO)	MNRF for nanometric analysis of structure and chemistry of physical and biological materials. www.nano.org.au/
INSTITUTIONS	**DESCRIPTION**
Australian Universities	A wide range of nanotechnology-related University Centres and Institutes as well as research teams. Much nanotechnology research is supported by competitive funding through the ARC. Some bionanotechnology work is also supported by competitive funding through the NHMRC.
CSIRO Divisions of Telecommunications. & Industrial Physics, Manufacturing and Infrastructure Technology, Forestry Products	CSIRO Divisions of Industrial Physics, Manufacturing and Infrastructure Technology, Forestry and Forestry Products, Livestock Industries, Health Science & Nutrition, Textiles, Molecular Science are engaged in nanotechnology research, spanning areas that include nanostructured materials, nanoelectronics, nanophotonics, medical diagnostics, biomimetic materials, membrane technologies and applied quantum systems.
DSTO	Nanotechnology research includes electronic fabrication, conducting polymers, electromechanical systems and laser machining for use in structural sensors and electromagnetic detection.
ANSTO	R&D areas include nanoparticles nanohybrid materials and membranes for a range of applications as biotechnology, optics and electronics and manufacturing. Facilities are used by other Australian scientists to characterise nanostructured systems. The OPAL research reactor comes online next year and will bring new nanotechnology research capabilities to Australia.

Australia's nanotechnology research is sustained by public investment which accounts for well over half of Australia's estimated investment in nanotechnology R&D of around $100 million per annum. At the commonwealth level, expenditure from the Education, Science and Training portfolio was estimated at over $50 million in 2002-03. In addition to funding through research agencies such as CSIRO and ANSTO, the Education, Science and Training portfolio funding is provided through the Australian Research Council's National Competitive Grants Programme, Research Infrastructure Block Grants, the Cooperative Research Centres programme, the Major National Research Facilities programme, the Systemic Research Infrastructure Initiative, and the International Science Linkages Programme. There are more than 200 current nanotechnology-related ARC Linkage projects, as well as a number of NHMRC grants and fellowships, and several Federation Fellows.

Issues and challenges for the research sector

Whilst Australia's nanotechnology research base has world-class capability in key areas, it is necessarily small by global standards. Our ability to impact on technologies that may become important for industry on the 10 year timescale and beyond — such as molecular and nano electronics, nano optoelectronics and nano photonics, Lab-on-a-Chip, carbon nanotubes, fuel cells and Nano Electro-Mechanical Systems (NEMS) — will require continued long-term funding of basic cutting-edge Australian science. But at the same time, strategic international links will be crucial as nanotechnology research becomes increasingly expensive, complex, multidisciplinary and dispersed internationally.

It will also require some consolidation and coordination of the research effort as well as improved linkages between public sector researchers and industry to accelerate commercial application of Australia's nanotechnology research.

Research clusters involving cutting-edge public sector research, well linked to industry and international centres of excellence will be one important means of achieving this. Several such clusters are already developing in Australia, as illustrated in the following box.

Whilst innovation in certain areas of research, for example nanopowders, can be captured by Australian enterprises in the short term, the biggest impact of nanotechnology will be in industry sectors that require substantial investment in prototyping facilities. There is therefore a need for a forum that addresses the critical research–industry interface, to identify and prioritise Australia's infrastructure and training needs.

Finally, there is a need for government and non-government structures to allow the significant effort in Australia to be catalysed. These include structures which promote communication across government departments and agencies and with industry. Close cooperation between national and state agencies to build a coordinated effort in nanotechnology is now needed.

Two examples of Australian nanotechnology research clusters

The Nano Electronics and ICT Research Cluster

The ARC Centres for Nanostructured Electromaterials, Quantum Computer Technology and Quantum Atom Optics, together with the Bandwidth Foundry, the NANO MNRF and several Australian universities including ANU provide a strong Australian research base in electronics/photonics and in the emerging areas of quantum communications and quantum computing. This base has attracted interest and investment from several major US computer firms (Hewlett-Packard and Intel), and also provides support for a generation of start-up firms which leads commercialisation of advances in atom electronics.

Ian Wark Research Institute (The Wark™)

The Wark™ is the leading Centre in the science of particle and mineral interfaces in Australia and a leader in the field internationally. It boasts the ARC Special Research Centre for Particle and Material Interfaces as well as a Nano and Biomaterials Centre with extensive overseas collaboration. The Wark™ is unusual in its creative and flexible approach to R&D where a mixture of fundamental and applied research is conducted across a wide range of project areas, in collaboration with a large number of industry and research partners. It is proving to be a magnet for a range of companies as illustrated by the following quote from Dr Megan Clark, VP Technology BHP Billiton:

'The Wark™ is one of only three institutes in the world that we are working with that is positioned for breakthroughs in science relevant to several industries. The institute has world class capability and its focus on particle and surface interactions has the potential to lead the way in industries outside the minerals sector, including the pharmaceuticals, optical, and the food industry.'

3.2 Private sector — nanotechnology in Australian industry

Nanotechnology has been applied in mainstream industry for some time in companies such as Buhler AG, BHP Billiton, Orica and Rio Tinto. For example, nanostructured catalysts have been used for decades in petroleum refining — zeolites, catalytic minerals that occur naturally or are synthesised, have a porous structure that is often characterised on the nanoscale.

In some of these companies, nanotechnology is recognised as a natural extension of their core technology and an integral part of their strategic research planning, while other companies see that they will be users of nanotechnology but not developers of R&D. On the other hand, smaller firms tend to be unaware of nanotechnology's possibilities for their business.

At least some of the companies surveyed by the working group recognised that nanotechnology has the potential to change traditional industries as well as create new ones. They also offered the following perspectives:

- A big issue will be the perceived risks of nanotechnology by the common population. The last thing that industry wants to happen is for nanotechnology to be treated like genetics and biotechnology preventing real innovations in the market for a very long time.

- Australia should focus their efforts in areas where it can make an impact and this should be where there is already existing mainstream industry — it is difficult to grow a business if there is no industry to take it up.
- Any Australian research effort needs to be coordinated, leveraging off other national and international projects and directed at providing commercial solutions.

On the whole, however, there would appear to be limited knowledge within mainstream Australian industry of nanotechnology and the opportunities it presents, as evidenced by a recent University of Western Sydney survey of regional Sydney industry.[36]

Apart from applications in mainstream industry, nanotechnology forms the core focus for a limited but growing industry base in Australia. Over 30 Australian nanotechnology-based firms have been formed during the last 5 years, covering such applications as new materials and particles, medical and pharmaceutical devices and processes, environmental and agricultural filters and sensors, and miniature batteries and capacitors. There has been very little venture capital investment in these innovative firms to date.

There are five industry sectors where Australia has significant nanotechnology opportunity, based on the improvements available through current technology developments. These are minerals and agribusiness; medical devices and health; energy and environment; advanced materials and manufacturing; and electronics and information and communications technologies. The table below summarises current activity in each of these sectors, and the future development opportunities available through nanotechnology.

It can be seen from the table that nanotechnology offers a range of opportunities to Australian industry from improved separation technologies for the mining industry, to better agricultural waste management and food safety, as well as nanoparticle applications in cosmetics and sunscreen agents, paint additives and catalysts. Australia also has capabilities in structured nanocomposites for aerospace and automotive applications and in the molecular design of water purification and gas separation units for domestic and commercial use.

Government funding for industry R&D in nanotechnology is sourced largely through the Department of Industry Tourism and Resources (DITR). Funding from DITR in support of industry uptake of nanotechnology is estimated at over $4 million in 2002-03, mainly through IR&D Board innovation grants, tax concessions and other industry-focused initiatives[37]. However, most of the grantees to these programs are small start-ups rather than mainstream industry. This observation is consistent with evidence from submissions that there is low awareness of nanotechnology in Australian industry.

At the state government level, Nanotechnology Victoria (Nanovic) was set up as consortium by three Victorian universities (Monash, Swinburne and RMIT) and the CSIRO with the support of the Victorian government. It is underwritten by a pre-venture capital fund set up by the Victorian government to commercialise nanotechnology innovations, worth $12 million over three years, together with $16 million from the consortium.

36 http://www.uws.edu.au/nano

37 Industrial Research and Development Board submission to the working group, November 2004.

Nanotechnology applications and opportunities in Australian industry

Sector	Company	Current Applications	Future Opportunities (5-10 years) for the Sector
Mining & Agri-business	• Advanced Nanotechnology • Mindata • BHP Billiton; Rio Tinto	• Alumina platelets • Separation • Bioextraction; applications for particles, oxide powders	• Bio-leaching processes; mining without surface disturbance • Processes to eliminate tailings and mine wastes • Food process control systems to eliminate contamination • New taste and nutritional delivery systems
Energy & Environment	• Very Small Particle Co. • Advanced Nanotechnology • Ceramic Fuel Cells • Cap-XX • Memcor • Nanoquest Pty Ltd	• Industrial catalysts • Fuel additives • Solid oxide fuel cells • Supercapacitors • Membrane separation • Water/air purification, fuel cells/hydrogen technologies	• Artificial photosynthesis; efficient energy from light • Paint-on solar cells • Membranes for bulk water desalination & purification • Particles to rapidly purify air • Silica membranes for H2 separation, photocatalysis
Health & Medical	• AMBRI • Starpharma • Eiffel Technologies • pSivida • MiniFAB	• Diagnostic markers • Dendrimer drug delivery • Particle engineering • Biosilicates for tissue engineering • Lab-on-a-chip devices	• Real-time ultra-sensitive diagnostic devices • Point-of-care medicine • Personal monitoring • In-vivo applications: new surfaces and materials to replace or repair tissues
Materials & Manufacturing	• Orica • Bottle Magic • Advanced Nanotechnology • Micronisers	• Coatings; catalysts • Coatings for food protection • ZnO in paints, sunscreens • ZnO in sunscreens	• Advanced sensory and control processes for manufacturing systems • Textiles with electronic and new mechanical properties • High-performance structural materials • New abrasives, lubricants • Intelligent packaging
Electronics & ICT	• Peregrine Semiconductors • Wriota • Quantum Precision Instruments • Advanced Display Technology • Qucor	• Semiconductors • Memory applications • Positioning devices • Flexible displays • Atom-scale nanoelectronics	• Organic computers; integration of IT and biological systems • Parallel computing capacity • Computing and tele-communications systems • Energy-conversion and lighting systems with greater efficiency

Challenges for Australian industry over the next 20 years

Australian industry is already incorporating nanotechnology into a range of products, and will continue to do so effectively through incremental advances in nanotechnology. The challenge will be for Australian industry to capture some of the longer-term, disruptive innovations that have the capacity to transform current technologies and create entire new industries.

This will require much greater uptake of nanotechnology by mainstream Australian industry as well as the growth of an innovative range of nanotechnology focused SMEs. Because most Australian nanotechnology is driven by academic research, links between industry and the public sector research base need to be enhanced if Australia is to capture the full economic potential of this transforming technology.

It will also depend on continued commitment by the Australian Government to:

- support fundamental nanoscience research over the long term (to underpin the discovery and development of disruptive innovations)
- ensure that Australia has the full complement of infrastructure needed to underpin a global competitive position in nanotechnology (see section 3.4)
- provide the necessary technical and business training opportunities to underpin the human resource requirements of this new technology.

Finally, Australia lacks a comprehensive framework for promoting industry activities in this area. Invest Australia has adopted nanotechnology as a priority area for attracting inwards investment and there are several state initiatives aimed at promoting commercialisation of nanotechnologies[38]. However, the private sector needs to create a collective voice for the emerging nanotechnology industries and develop a range of strategic initiatives to support and strengthen the nanotechnology business community.

3.3 Examples of Australian nanotechnology innovations

As indicated earlier in this chapter, Australia has world-class capability in the area of nanomaterials, quantum-based nanotechnology and in nanoelectronics/photonics, with applications across a range of sectors. This can be illustrated by the following examples of important Australian nanotechnology innovations.

Nanobiotechnology: the power of converging sciences

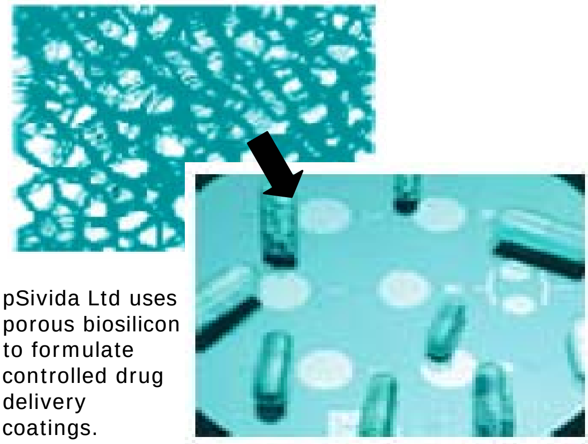
The engineering of nanoscale materials is important in biological systems because most of the critical biological interactions are on the nanoscale. By integrating biology with electronics, particle chemistry and information technology, nanobiotechnology offers solutions to many challenges in drug development, diagnostics, food production and processing, as well as environmental remediation.

Australia has significant capability across the three major areas in which the advances of nanotechnologies have direct application to biological industries:

- nanoscale delivery mechanisms to transport agent to a target site
- nanomaterials with improved biological functions — such as food additives to improve flavour or texture and to improve shelf life
- nanosensors to detect substances such as pathogens, diseased cells, poisons and contaminants, better identification of diseases such as breast cancer and applications for remote sensing (eg for crop management and food safety).

38 Invest Australia *Nanotechnology Australia – Capability & Commercial Potential*, Australian Government, Canberra, 2004 www.nanotechnology.gov.au (accessed 1 February 2005).

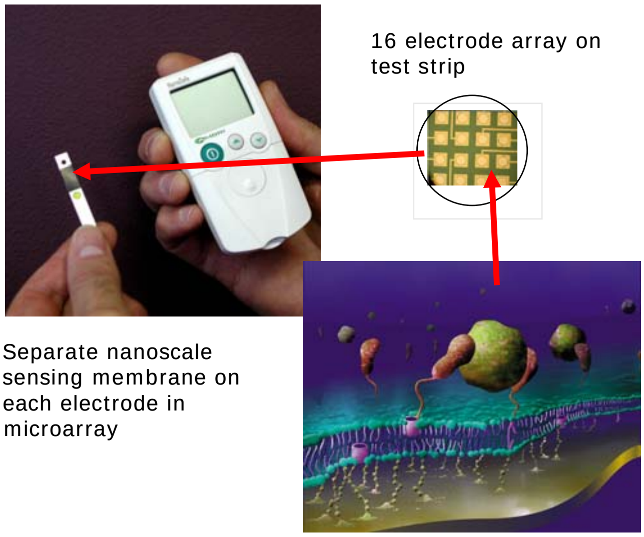
Examples of Australia's achievements in nanobiotechnology include the pSivida BioSilicon™, a new nano material for drug delivery, and the Ambri Ion Channel Switch for point-of-care diagnostics. These are illustrated in the boxes below.



pSivida Ltd uses porous biosilicon to formulate controlled drug delivery coatings.

pSivida Ltd BioSilicon™

As a new biomaterial, BioSilicon™ is a nanostructured form of elemental silicon, engineered to create a 'honeycomb' structure of pores. This structure allows silicon to biodegrade while also retaining various drugs and vaccines within the honeycomb matrix. BioSilicon™ retains the key semiconductor properties of silicon and is machineable at a micro level. BioSilicon™ also demonstrates optical properties that provide the basis for a variety of potential devices for biodegradable and biocompatible diagnostic products.



16 electrode array on test strip

Separate nanoscale sensing membrane on each electrode in microarray

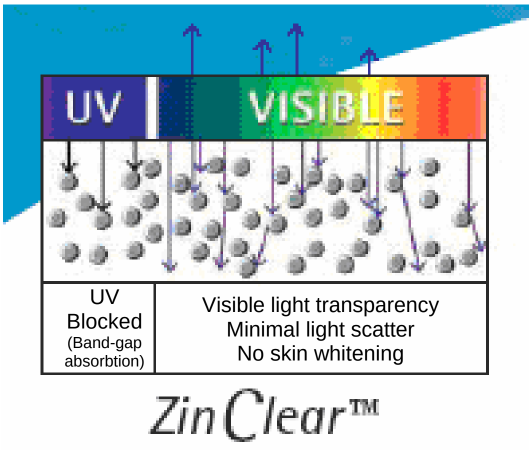
Ambri Ltd Ion Channel Switch (ICS™)

The Ambri ICS™ is the first purpose-built nano-machine operating with nano-scale moving parts. The ICS consolidates more than a decade of research by the Australian Membrane and Biotechnology Research Institute (AMBRI), CSIRO and the University of Sydney. The company, Ambri Ltd is incorporating this technology into a reader and a series of test-specific, single-use disposable cartridges for point of care diagnostics, as well as other markets.

New ways to manufacture nanoparticles

Nanoparticles and materials have a myriad of applications such as cosmetics, coatings, pharmaceuticals, health care, catalysts and advanced ceramics, as well as agribusiness uses in fertilisers, herbicides, cleaning and purifying agents. Australia has considerable strength in this area. For example, the University of Queensland has developed a novel technique for making porous oxides with large surface area and controlled porosity. An example of the use of such materials is a water purifier utilising solar energy driving the total elimination of contaminants on photocatalytic nanoporous particles. As a second example, The Very Small Particle Company Pty Ltd in Brisbane has discovered a process for producing a wide range of metal oxides with advanced properties with applications including fuel cells, batteries, electronics and catalysts. Yet a third example stems from research at the University of

Western Australia. A ball mill normally used for simple grinding and mixing using mechanical energy has been adapted to stimulate chemical reactions at the nanoscale, resulting in a totally new way to manufacture nanoparticles. Advanced Nanotechnology Limited has adapted this technology to the commercial manufacture of nanopowders (see box below).



Cosmetic clarity and the efficiency of Zinc Oxide in blocking UVB and UVA are directly related to particle size, size distribution, particle loading and dispersion.

Advanced Nanotechnology Limited

Advanced Nanotechnology has built on research at the University of Western Australia in commercialising a patent protected mechanochemical nanopowder manufacturing technology (MCP™).

The MCP™ technology enables the production of a broad range of nanopowders with potential to penetrate emerging global markets in areas such as cosmetics, industrial coatings, pharmaceuticals, health care, catalysts and advanced ceramics. Initial products include transparent zinc oxide dispersions for UV protection, platelet alumina powders used in cosmetics and nano cerium oxide dispersions for environmental applications.

World-leading, high power density supercapacitors

Ground-breaking research from CSIRO and Energy Storage Systems led to the design and manufacture of supercapacitors — high-power, high-energy storage devices that use nanostructured colloidal carbon electrode materials. Supercapacitors enable manufacturers to make smaller, thinner and longer-running products such as mobile phones, portable wireless data terminals, medical devices, automatic meter readers, and digital cameras. Australian company, cap-XX has capitalised on this technology to become a world leader in superconductor manufacture and marketing (see box below).

A cap-XX supercapacitor

cap-XX Pty Ltd

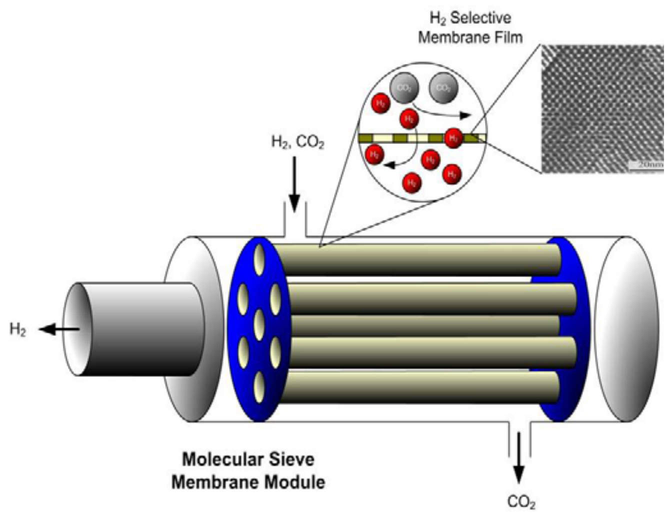
cap-XX is an Australian company incorporated in 1997. It focuses on developing and commercialising advanced supercapacitors (high-powered energy storage devices). Supercapacitors work by employing nanostructured colloidal carbon electrode materials, which help to store energy by way of nanometre-wide pores. As a result of their leading technology and high quality product, cap-XX is expected to dominate the supercapacitor market, which some forecasters predict will eventually exceed US$6 billion. cap-XX is expanding globally and has sales staff based in the USA and Taiwan.

The development of single atom nanoelectronics

The Centre for Quantum Computer Technology has constructed semiconductor devices engineered with single atom precision that offer sensitivity approaching the quantum limit. Such devices offer a pathway to the development of solid-state quantum computing (relevant to national security), single atom memory.

Nanoporous membranes for clean hydrogen generation from coal

Efficient separation of molecules using molecular sieve membranes offers tremendous potential for separating carbon dioxide from flue gases or hydrogen from other gases so that carbon can be sequestered while producing a pure stream of hydrogen from fossil fuels. Australia has cutting edge science critical to development of porous, highly selective nanomaterial membranes for this purpose as illustrated in the box below. It is an example of Australia's window of opportunity in key frontier technologies with the potential to make a very significant contribution to the efficiency and economics of coal sourced hydrogen production.



Nano-membrane separation of H_2 and CO_2

Researchers at the University of Queensland have developed nanoporous membranes that can efficiently separate CO_2 from H_2. This has the potential for a major breakthrough in clean hydrogen generation from coal.

The diagram shows a H_2/CO_2 mixture entering a tube containing a sieving membrane. Only the small (red) H_2 molecules pass through the gaps.

3.4 Infrastructure needs

In implementing national strategies for nanotechnology, countries such as the USA and UK have recognised the importance of major infrastructure as well as the need for continued upgrading in order to remain at the cutting-edge in such a fast moving field. For example, the UK Micro and Nanotechnology Manufacturing Initiative[39] committed £40 million of a total £90 million in government funds towards facilities development in bionanotechnology, metrology and analysis, fabrication, nanomaterials and micro-electromechanical systems.

The 1999 PMSEIC report on nanotechnology[40] noted that commercialisation infrastructure was absent in Australia, and that a national toolbox of nanotechnology facilities be established. Notwithstanding major recent initiatives such as the Synchrotron and the ANSTO OPAL research reactor, the findings and recommendations of the 1999 report are still pertinent.

39 www.dti.gov.uk/nanotechnology

40 *Nanotechnology – the Technology of the 21st Century: The Economic Impact of Emerging Nanometre Scale Technologies*, prepared by Dr Bruce Cornell and Dr Leong Mar, November 1999 (www.dest.gov.au/science/pmseic/documents/Nanotech.pdf).

Australia will need to ensure that it has the full complement of infrastructure needed to underpin a globally competitive position in nanotechnology — characterisation tools, nanoscale science, molecular level computations and fabrication and processing technology (see section 2.2). In view of the limited understanding of nanotechnology in the private sector, Australia will also have to develop strategies to enhance industry's uptake of its research infrastructure.

There does not appear to have been a systematic evaluation of infrastructure needs at the national level. However, Nanovic has recently reviewed the need for new infrastructure and facilities for its members (Monash, CSIRO, RMIT, Swinburne) as well as Victorian industry. This has identified a need for prototyping and analytic facilities in the research sector, while industry has an unmet need for demonstration capabilities, prototyping, scale-up manufacture, and skills.

The working group suggests that the National Collaborative Research Infrastructure Strategy be used to address these needs.

The metrological (system of measures) support for nanotechnology development also needs to be considered. Considerable resources are being directed to this area by overseas governments because of the unique demands of measurements at the nanometre scale. The ability to measure accurately at this scale will also be crucial to the development of sound regulatory frameworks.

3.5 Education and skills

The expectation that nanotechnology will underpin many future developments across most industries has important implications for skills development across the whole education sector.

Science teaching must incorporate the broad brush of tools required for this convergent technology. Students will need a strong understanding of fundamental sciences such as physics, chemistry, biology, information technology but importantly must also appreciate the cross disciplinary applications that underpin nanotechnology.

At the tertiary level, this need is being addressed by some universities through specific nanotechnology degrees and courses. For example, undergraduate and postgraduate nanotechnology courses are either on offer already or planned for universities such as Flinders University, the University of New South Wales, the University of Technology Sydney, the University of Queensland, RMIT University, University of Wollongong, the University of Western Sydney, Deakin University, University of Western Australia and Monash University. These courses are demonstrating varying success in attracting students. Perhaps a more successful approach will be the integration of science courses which underpin nanotechnology in a way that enables students to appreciate the cross disciplinary nature of nanotechnology.

In terms of vocational training, there are limited opportunities for training to provide specific skills in support of nanotechnology within the Technical and Further Education system in Australia. The Australian Government has commissioned an industry-led Emerging Technologies Taskforce to facilitate and expedite activities to: identify industry and individual skill needs of the industries using emerging technologies including nanotechnology; develop appropriate training products and services; and increase provision of training/skilling opportunities and promote their uptake. The taskforce is due to provide an interim report at the end of March 2005 and a final report in July 2005.

The challenges for nanotechnology at the secondary school level reflect the deficiencies apparent across the whole of science training and should be addressed in this context.
Because of its cutting-edge and topical nature, nanotechnology offers schools a tool with which to promote science as an exciting career opportunity for students.

In summary, the development of a substantial Australian skills base in nanotechnology is of fundamental importance. The requirement for this skills base will continue to grow over the next 10 to 15 years.

3.6 Public awareness

A survey of community perceptions commissioned by the Department of Industry, Tourism and Resources indicated that 46% of respondents had heard of nanotechnology (mostly from news stories or television, and in the context of miniaturisation) but only 28% could name possible applications (electronics, computers and environmental). Only one to two percent of respondents saw benefits or had concerns about nanotechnology specifically. In contrast, in the context of advances in science and technology in general, 58% percent of respondents saw benefits from nanotechnology (improvements in health care and quality of life) compared to 18% who had concerns (mostly loss of privacy, adverse environmental impacts and unforseen side effects). The survey also found that 49% of respondents wished to be consulted about nanotechnology developments, mostly in the context of general advances in science and technology[41].

These results mirror the findings of a survey commissioned by CSIRO in regional Victoria, which indicated that public engagement is crucial to widespread acceptance of the benefits flowing from nanotechnology[42]. It was felt that adequate resources and infrastructure are required to engage the community in nanotechnology issues and that public education programs involving ‘credible’ advocates openly addressing public concerns and outlining key issues should be implemented. Such concerns include intrusions into privacy and loss of personal freedoms from security measures.

This level of awareness and the concerns of the Australian community are consistent with that in other developed countries.

Several organisations, notably CSIRO, Questacon and universities are taking steps to increase community awareness of nanotechnology, although much more needs to be done. A model house (The Nanohouse) jointly developed by CSIRO and the University of Technology Sydney with seed funding from the Australian Government Department of Industry, Tourism and Resources, shows how new materials, products and processes emerging from nanotechnology research and development might be applied to our living environment.

41 Market Attitudes Research Services Pty Ltd, *Short report: Australian community opinion towards nanotechnology and the commercialisation of scientific research*, 26 November, 2004.

42 Mee, W., Lovel, R., Solomon, F., Kearns, A., Cameron, F., and Turney, T. (2004) *Nanotechnology: The Bendigo Workshop*, Report DMR-2561, CSIRO Minerals, Melbourne October 2004.

http://www.nano.uts.edu.au/nanohouse.html

The Nanohouse

The Nanohouse has an energy-efficient radiative cooling paint as the outer surface of some of the roofing material, which becomes a cooling element rather than a source of unwanted heat gain. Other features are sustainability, self-cleaning glass, cold lighting systems and dye-sensitised solar cells.

3.7 Health and environmental impacts

Acceptance of products incorporating nanotechnologies may be held up by concerns about occupational health and safety issues for workers in manufacturing sites, by market acceptability and safety issues for consumers who ultimately may purchase nanotechnology-enhanced products, by environmental safety issues and by fears of disruption to society.

For example, Australia is already manufacturing nanoparticles. Submissions noted the unknown toxicology of nanopowders compared to their macro forms, and questioned whether our current regulatory systems need to be modified. They also emphasised the need for research into the safety of nanomaterials needs to keep up with their commercialisation.

Submissions to the working group also raised a number of examples of the potentially disruptive impact of nanotechnology on Australia. An example is the impact on the pathology and medical diagnostics sector, whereby patients may be provided with access to point-of-care testing and diagnosis via nanotechnology developments. If adopted generally in Australia, this change will have a major impact on the firms and personnel currently providing services to this sector.

These concerns mirror those that are apparent at the global level and highlight the need for a comprehensive impact and risk analysis framework. This framework must adopt a science-based risk identification, assessment and management process.

Australia's regulatory system, in particular the National Industrial Chemicals Notification and Assessment Scheme (NICNAS), the National Occupational Health and Safety Commission (NOHSC) and the Therapeutic Goods Administration (TGA), are the appropriate agencies through which to structure such a framework. The TGA indicated in a submission to the working group[43] they are committed to following through on establishing criteria/guidelines for the safe use of nanoparticle technology in its application to therapeutic goods. NICNAS and NOHSC noted, in their joint submission[44], that the challenge for regulators is whether the

43 Therapeutic Goods Administration (TGA) submission to the working group, November 2004.

44, National Industrial Chemicals Notification and Assessment Scheme (NICNAS) and National Occupational Health and Safety Commission (NOHSC) joint submission to the working group, Novermber 2004.

current safety and risk assessment framework can be applied to nanotechnology or whether a new risk assessment paradigm will need to be developed. Moreover, metrology issues underpin regulatory frameworks, and the National Measurement Institute notes that it is well-positioned to support nanometrology programs in the future.

In addition to regulating the Australian developments these agencies will need to keep appraised of international developments in the regulation of nanotechnology, particularly through the OECD and other international forums. It is likely that development of a regulatory framework for nanotechnology will require consultation and coordination between a number of commonwealth portfolios and agencies, and between commonwealth and state authorities.

It is crucial that Australia, as part of an international effort, proactively addresses these emerging issues concerning community awareness and acceptance of nanotechnology, as well as the considerable ethical, social and safety implications. Where environmental and human health impacts have not been studied and are therefore unknown the applications of the technology need to be assessed on a case-by-case basis by the appropriate body. Australia's regulatory system should be examined to evaluate its capacity to meet these needs.

The early introduction and explanation of regulation reduces the risk that public concern will prevent acceptance of nanotechnology. Industry also tends to prefer certainty in regulation rather than having to make business decisions in an uncertain environment with a possibility of regulation being imposed in the future.

3.8 The need for a national strategy for nanotechnology

The Australian Government's *Backing Australia's Ability: Building Our Future Through Science and Innovation* initiative launched in 2001 constitutes an $8.3 billion integrated 10-year commitment to science and innovation[45]. As part of this commitment to innovation, Australia identified four National Research Priorities that guide the investment of the public funding of research towards areas of major opportunity and challenge. Given the enabling and broad nature of nanotechnology, it can be argued that nanotechnology underpins each of these priorities. Nanotechnology has also been identified as an example technology under the *Frontier Technologies for Building and Transforming Australian Industries* National Research Priority[46].

Notwithstanding the inclusion of nanotechnology in the National Research Priority goals, Australia has yet to develop a national strategy for this important technology. This contrasts with a number of other countries such as USA, UK, and Ireland which have in place comprehensive and broad-ranging nanotechnology initiatives[47].

The situation Australian nanotechnology faces at this time is similar to that encountered by the biotechnology and ICT sectors a decade ago — with the industry component characterised by small, under-capitalised emerging business enterprises limited by lack of access to prototyping facilities within Australia, a growing academic research capability, which is showing signs of a collaborative approach, and several state government investment

45 http://backingaus.innovation.gov.au/default2004.htm

46 http://www.dest.gov.au/priorities/transforming_industries

47 http://www.nano.gov/; www.dti.gov.uk/nanotechnology

initiatives into nanotechnology. There is also commonality with biotechnology in terms of community concerns with public safety associated with new technologies.

The Australian Government addressed the biotechnology situation by the implementation in 2000 of an Australian National Biotechnology Strategy with the following aims (paraphrased):

- Ensure that in research into, and in applications of biotechnology, human health and the environment are safeguarded, and the highest ethical standards are observed
- Ensure the community has access to quality information about biotechnology, has confidence in the way risks are assessed and managed, and can contribute to public policy in this area
- Enhance the economic and community benefits of biotechnology through investment, science-industry linkages and management of IP
- Maintain and develop infrastructure for generating biotechnology applications through investment in R&D, education, and securing access to, and conserving, genetic and biological resources.

A 2003 review of the strategy's implementation noted the following challenges still need addressing (paraphrased):

- The strategy requires deeper involvement by the states and territories if it is to be truly national
- Further efforts to maximise commercial and social benefits
- Further initiatives to keep the community engaged in an informed debate on ethical and consumer issues
- Further efforts to manage potential risks to the environment.

The opportunities for economic growth through a vibrant nanotechnology sector in Australia are significant if the challenges outlined above can be met and there is acceptance by the public of nanotechnology enabled products. The time appears ripe for the formation of a nanobusiness alliance with the help of government to assist, within the appropriate infrastructure and regulatory environment, the growth of SMEs engaged in nanotechnology R&D and the implementation of nanotechnology R&D strategies within mainstream firms.

3.9 Conclusions

Nanosciences and nanotechnologies are starting to have an impact on our everyday lives with the potential to become important drivers for Australia's international competitiveness.

It is possible nanotechnology will transform mainstream Australian industries as well as create whole new industries through disruptive technologies.

Australia now has substantive research and an emerging SME nanotechnology sector. In addition some mainstream Australian businesses have developed comprehensive nanotechnology strategies. Australia is globally competitive in particular areas as evidenced by world-leading technologies being developed for diagnostic devices, nanomaterials, quantum computing and energy storage. Our nanotechnology R&D is already making significant contributions to mainstream industry, and Australian industry will become increasingly reliant on nanotechnology solutions over the next 5-10 years.

If Australia is to remain a global player in the development of nanotechnology-based industries we must understand that nanotechnology will become more expensive, complex, multidisciplinary and dispersed.

To capitalise on the opportunities offered by nanotechnology the challenge is to enhance the coordination of Australia's nanotechnology effort and the strategic concentration of resources.

The working group identified the need for government and non-government initiatives to catalyse the significant effort in Australia. Long term support of Australian fundamental nanoscience research will be required as well as some consolidation and clustering of research effort. Australia will need to be well-integrated into international efforts.

Mechanisms are needed to support and strengthen Australia's fledgling nanotechnology industry as well as enhance industry links with the public research sector. The competitiveness of Australian industry will also require a full complement of infrastructure — characterisation tools, nanoscale science, molecular level computations and fabrication and processing technology. A lack of prototyping facilities is a particular impediment for industry development.

It is crucial that we have in place the appropriate frameworks for coordination, regulation, training and education to ensure successful industry uptake and to address the issues at the research, industry and community levels. The development of a comprehensive impact and risk analysis framework must be seen as a high priority.

To address these findings the working group recommends that consideration be given to the development and implementation of a national nanotechnology strategy under a coordinated framework which covers investment in basic research and key infrastructure, industry development, monitoring of the risks associated with products enabled by developments in nanotechnology as well as addresses public concerns regarding nanotechnology-enabled products.

In conjunction with a national nanotechnology strategy the working group recommends that an Australian nanotechnology business alliance be formed with government support whose role is to overcome the current fragmentation evident in the nanotechnology sectors as well as link business and researchers. An industry alliance of this kind would provide benefits including fostering cross sector collaboration and links, building confidence of the investment community, facilitating the adoption of regulatory frameworks, enhancing the uptake of nanotechnologies solutions in mainstream industries, and driving the convergence of traditional disciplines that will give rise to disruptive innovations.

Appendix 1 — Submissions to the working group

Submissions were received from:

Asia Pacific Nanotechnology Forum
Australian Academy of Science
Australian Nuclear Science and Technology Organisation
Australian Research Council
Council of Textile & Fashion Industries of Australia
Defence Science Technology Organisation
Department of Agriculture, Fisheries and Forestry and Bureau of Rural Sciences
Department of Health and Ageing
Department of the Environment and Heritage
Federation of Automotive Products Manufacturers
GeneEthics Network
Greenpeace Australian Pacific
Institute of Materials Engineering Australasia Ltd
Industry Research and Development Board
Medical Industry Association of Australia
National Health and Medical Research Council
National Industrial Chemicals Notification and Assessment Scheme and Office of the National Occupational Health and Safety Commission
National Measurement Institute
New South Wales Government Department of State and Regional Development
Plastics and Chemicals Industries Association
Science Industry Australia
Therapeutic Goods Administration
Victorian Government Department of Innovation Industry and Regional Development
Questacon, The National Science and Technology Centre
Arnold Ward
David Ansley and Associates
Dr Judy Carman, University of Adelaide
Gillian Blair
Professor Gordon Parkinson, Curtin University
Professor Greg Tegart, Victoria University
Professor John Weckert, ARC Centre for Applied Ethics
Professor John White, Australia National University

The working group also received input from:

BHP Billiton, Bühler AG, Tenix, Orica Australia Pty Ltd, Rio Tinto, Stanwell Corporation Limited, Micro and Nanotechnology (MNT) network UK, Intel (USA).