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Paper Title: The race is not to the swift: breakthrough technology commercialization and implications for public policy

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The race is not to the swift: breakthrough technology commercialization and implications for public policy

Abstract
This research investigates the commercialisation of breakthrough technologies from science base to viable commercial applications. Breakthrough technologies emerge from novel and discontinuous innovations that result in significant and irreversible changes. These innovations are based on new, under-or un-exploited physical, chemical and biological phenomena that allow order of magnitude improvements in the performance of existing products and/ or the creation of entirely new ones. These novel innovations may entail the development of 'new technology platforms' with applications across a range of products and markets. Many of the resultant applications are not envisaged at the time of the initial innovation.

This paper summarises results from seven historical case studies of breakthrough technology development. The case study technologies are Liquid Crystal Displays (LCD), Light Emitting Diodes (LEDs), Optical Fibres, Photovoltaics, Inkjet Printing, Giant Magnetoresistance (GMR) and Microelectronic Mechanical Systems (MEMS). The case studies illustrate the dramatic changes breakthrough technologies can make on the industrial landscape and the context surrounding discovery and commercialisation of these technologies. The potential for extensive industrial development; enhanced national competitiveness; and employment and export growth are the key motivators for government activity in breakthrough technology development. These upside gains can outweigh the downside risks of commercialising these technologies and the knowledge that most of these attempts at breakthrough technologies will come to nothing.

Introduction
'The race is not to the swift, nor the battle to the strong, neither yet bread to the wise, nor yet riches to men of understanding, nor yet favour to men of skill; but time and chance happeneth to them all.' Ecclesiastes 9:11 Quoted by George Heilmeier in his acceptance speech on receiving an award for his pioneering work in LCDs, Tokyo, 1990 (Johnstone 1999, p.88)

The commercialisation of breakthrough technology is a rare event, yet when it does occur it can have dramatic effects on the industrial landscape. When and where the next breakthrough technology will emerge is difficult to predict because the extent and reach of the disruptive capacity of a new scientific discovery is unknown, as is the range of applications that such a discovery can change or create.

Breakthrough technologies emerge from novel and discontinuous innovations that result in significant and irreversible changes. These innovations are based on new, under-or un-exploited physical, chemical and biological phenomena, that allow order of magnitude improvements in the performance of existing products and/ or the creation of entirely new ones. These novel innovations may entail the development of 'new technology platforms' with applications across a range of products and markets. Many of the resultant applications are not envisaged at the time of the initial innovation.

Public policy in recent decades has attempted to encourage the *discovery* of breakthrough technologies and *accelerate* the commercialisation of these technologies. Government's may have invested heavily in the science behind these technologies; through the training of the highly skilled staff that work in both public and private research and development labs; through the provision of subsidies and grants to encourage R&D activity; and the use of public procurement, where the government acts as the first key customer.

This public policy interest in following and trying to support these technology activities lies in their enormous potential for value creation across a broad range of industries and applications (Maine and Garnsey 2006). New industries can create new employment, new export incomes and increase individual country's international competitiveness. These upside gains of income and employment can outweigh the downside risks of commercialising breakthrough technology and the knowledge that most of these attempts at breakthrough technologies will come to nothing.

This paper summarises results from seven historical case studies of breakthrough technology development. These case studies illustrate the dramatic changes breakthrough technologies can make on the industrial landscape and the context surrounding discovery and commercialisation of these technologies. The analysis of the emergence and development of breakthrough technologies encompasses the three inter-related areas;

Scientific discovery - the processes, people and organisations involved in the discovery of new, under or unexploited physical, chemical and biological phenomena.

Pre-commercial environment – where the science transfers into technology applications. The scientific discovery may have highlighted potentials for performance improvements of current technologies and/ or new technology platforms; understanding how these applications are identified and progressed is critical.

Commercial environment - the commercialisation of breakthrough technology particularly into brand new applications requires significant market development as well as the creation of suitable business models for exploitation. Commercialisation also requires the development of manufacturing capability to scale up production of the developed technology. All of these activities require successive cycles of innovation and have long timelines.

The commercialisation of technology from the science base is considered one of the key drivers of economic growth. This view is based on a combination of the recent US experience in high technology development and commercialisation (Hughes 1998; Chandler 2001; Kressel and Lento 2007) and evidence of large upscale profits achieved by successfully commercialising discontinuous innovations (Maine and Garnsey 2006). Successful commercialisation of science-based breakthrough technology can also have significant impacts on the national competitiveness of countries involved. The economic prowess of the US has been attributed to their success in developing high technology industries over the last five decades of the twentieth century (Nelson 1990).

Defining breakthrough technologies

Breakthrough technology is defined as;

Novel and discontinuous innovations that result in significant and irreversible changes and are based on new, under or unexploited physical, chemical and biological phenomena, that allow order of magnitude improvements in the performance of existing products and/ or the creation of entirely new ones. Breakthrough technologies may entail the development of 'new technology platforms' with applications across a range of products and markets.

This definition builds on, and encompasses a number of other terms that are used, often interchangeably, in the innovation and high technology management literature including; radical technology (Peters et al), radical innovation (Ettlie, Bridges et al. 1984; Utterback 1996; Grover, Purvis et al. 2007), architectural innovation (Abernathy and Clark 1985), disruptive technology (Christensen, Johnson et al. 2002; Kassicieh, Kirchhoff et al. 2002; Minshall, Seldon et al. 2007), non-incremental technical change (Freeman and Soete 1997; Nemet 2009), emerging technologies (Adner and Levinthal 2002), generic technology (Maine and Garnsey 2006) and revolutionary innovation (Kressel and Lento 2007). Although there are differences between these various terms, particularly in the time and circumstances of their use, the purpose of this brief overview is not to discuss the merits or contributions of each (see (Linton 2009) for a good overview of innovation terms), but to highlight consistent themes between all of these terms. The themes of irreversible change, new phenomena and the potential for radical and/or new industrial creation are encompassed by the majority of these terms. In this sense we believe that the definition used for this research offers adequate coverage of these themes.

This paper looks at breakthrough technologies that are sourced from the science base. This adds another layer of complexity to the commercialisation process. The vast majority of technologies can trace their roots to research in science, somehow and sometime. It is therefore important to distinguish what we mean by science based commercialisation.

Science-based commercialisation refers to the development of new to market technologies based on new scientific discoveries. The complexity of this process arises through a series of ‘unknowns’- how and when these discoveries will transfer into applications is unknown (Pavitt 1991) as is how they will change industrial composition and competitiveness (Tijssen 2002)and who will benefit from any resulting wealth creation (Kassicieh, Walsh et al. 2000). The functions and advantages of new science-based applications are unfamiliar to customers (Freeman and Soete 1997). Market feedback in the early stages of science based commercialisation is not available to guide the commercialisation process in the same way as exhibited in other areas of new product and service development. This can result in mismatched technology and market development.

The dichotomy between 'technology push' and 'market pull' is often used to highlights these differences. The emergence of technology via the ‘technology push’ pathway begins with scientific inquiry into specific phenomena. This in turn leads to speculative R&D work and potentially technological innovation. Market search then becomes the focus. In the 'market pull' version of technology development the process begins with a relatively well-defined technological need. R&D focused on developing applications to meet this need occurs and the resultant technological innovation, already with established market orientation, is commercialised into marketable applications. This is a simplified version of technology development, and the ‘technology push’ and ‘market pull’ pathways represent opposing ends of a spectrum of activity rather than two categories into which all technologies must fit. The pathways do however highlight different challenges facing technologies as they track to market.

The science-based technology breakthroughs investigated in this research fall more on the 'technology push' side of the spectrum in their initially stages of development. This is not to say that all emergent applications of these technologies will remain 'technology push'. In many cases they will be market driven. One of the tenents of the CIKC program is to more closely align the scientific-inquiry driven technology 'push' pathway with the market oriented ‘pull’ pathway.

The technologies discussed in this report are the result of development and engineering throughout a long period of pre-commercial development. The multi-varied paths of development that these technologies take can create the situation where “the greatest benefits are the least anticipated and surface many years later” (Tijssen 2002 p.509). Science based commercialisation success can be incidental and emerge from largely inconsequential (at the time) activities by a number of actors in the very early stages of the breakthrough technology's evolution - activities that are taken when the end result and any resulting profitable industry is a long way off. This is why understanding previous science based commercialisation, particularly the decision making processes involved for firms and other organisations about where and in what situations science is commercialised and the progress from science to technology application, is critical to inform future decision making.

The pathway of science based commercialisation includes three areas; the science base, the pre-commercial environment and the commercial environment. The points of transition between these three areas of activity provide the most illustrative units of analysis, so the movement of technology from the science base into the pre-commercial environment, and then from the pre-commercial environment to the commercial environment. This is illustrated in Figure1. The figure shows the pathway from the science base to the commercial technology environment. This pathway is intersected by a period of pre-commercial development, with the intersection points highlighting when technologies move into pre-commercial development and when they move out of this phase. The pre-commercial environment therefore is a critical junction in understanding the development of breakthrough technology.

Adner and Levinthal (2002) use the analogy of 'speciation events[1]' as used in evolutionary biology to understand this stop-start relationship in emerging technology commercialisation. They note technology evolution can either be a quick process with the new technology rapidly linked to applications (and demand for applications) or, be a long and slow process.

The two transition points can occur in two places (geographically) and at different times, (sometimes decades can elapse between the transition from science base to pre-commercial environment and then pre-commercial to commercial environment) for each application. The transitions also each require different sets of decision making and actors. The transfer to the commercial environment is heavily dependent on the resources available at that point of time (knowledge, financial, organisational and market) and the progress of other technological advances commercialising or being developed at the same time. Finally, the transition points are independent of each other, just because a technology transfers from the science base to the pre-commercial environment does not mean that a transition to the commercial environment will also necessarily occur.

Funding technology emergence

Commercialising breakthrough technology has demanding funding requirements. Funding needs to cover not only extensive periods of R&D but also market exploration and business development. Financial support for the commercialisation of breakthrough technologies is accessed from three main sources; Government, through research programs and grants; large firms, through their research and development programs; and thirdly various forms of external and risk capital. Increasingly, in recent times we can add a fourth category, small and medium sized firms funding technological development through revenue from R&D contracts for other customer firms (usually large firms).

The commercialisation process for most breakthrough technologies will access all of these. Yet as technologies develop, and specific applications emerge the composition of funding sources moves from public to private. The public good aspects of 'exploratory' or 'basic research' see public funds supporting the basic science period, private funding supports the majority of commercial environment development. The pre-commercial environment draws on different mixtures of public and private funding sources. The combination of funding sources leaves gaps in funding for some areas of development. This research investigates these changes in composition of funding and the associated risk and reward profile through the commercialisation process.

The role of public policy

Public policy over the preceding decades has attempted to encourage the discovery of breakthrough technologies and accelerate the commercialisation of these technologies. The public policy interest in supporting these technology activities is in the potential for industrial development. New technologies can create new industries or reinvigorate mature ones. These

[1] Adner and Levinthal (2002) define speciation events as the separation of one evolving population from its antecedent population, which in turn allows subsequent populations to follow different evolutionary paths.

new industries can have effects on export income and international competitiveness and increase knowledge based employment.

There are compelling reasons for investing in science and technology research, Nelson (1990) attributes US technological leadership for the majority of the last century to their increased investment in science and engineering either through higher education participation, university research or corporate R&D. Yet because of the long gestation period of many science-based technologies, particularly breakthrough technologies the rewards for such technological investments do not always accrue to those who make the investments.

Public policy has a role to play in every step of the science based commercialisation pathway. In the science base, public funds are the primary source for curiosity-driven and basic scientific research. In the pre-commercial phase public institutions, either government R&D labs or universities play a role in the research and development activities that support the continuing technology development. The funding mechanisms used by organisations in the pre-commercial environment are broader than in the basic research arena; they still include funding for Universities to carry out research but also include specific focused government funding programs, government R&D contracts for the development of specific types of technological applications. Also important are access to government scientific agencies and scientific equipment to test and measure new technologies (important in setting standards and establishing the credibility of competitive advantage of a technology with competing technologies), and government procurement and contracts which make government departments first customers for new technology applications.

Public policy interventions have focused on this pre-commercial environment, and activities that assist technology transition from the pre-commercial to the commercial environment. This is particularly evident in the past few decades. This has been done in a number of ways including, encouraging universities to patent, license and commercialise science based discoveries that emerge from their research. Other countries such as Germany and the Netherlands have developed intermediate institutions that offer an incubation space between universities and industry. In the US the *Small Business Innovation Research (SBIR)* programme has used government procurement funding to offer 100% upfront development funding for technology applications that can address government stated needs, therefore providing funding but also demand pull for any emergent technological application (Connell 2006). Other countries have sought to increase subsidies available to firms to invest in R&D, and subsidies to firms and individuals to invest in risk based investment opportunities - which are typically new technology based firms.

Historical case study methodology

This research uses a historical case study methodology. Earlier sections of this report have alluded to the advantages of this approach including the ability to deal with the complexity of analysis of technological development; the many participants, organisations and geographies. Also, historical analysis allows us to deal with the long timelines involved in technology commercialisation.

Historical analysis of past technology commercialisation also has relevance to current considerations of science commercialisation. As Tosh (1984) points out, "...we know that we cannot understand a situation in life without some perception of where it fits into a continuing process, or whether it has happened before...our sense of what is practicable in the future is formed by an awareness of what has happened - or not happened - in the past" (p.1).

Although the historical method allows comparisons to be drawn between the different development paths of breakthrough technologies and the role of different actors, organisations and government policies in these development paths, it is limited to describing and analysing what happened (or did not happen), not what could have happened if situations were different(NRC 1999). The method also has the advantage of hindsight. A further limitation is that the economic, commercial and institutional environment has changed since our earlier cases.

In order to identify a group of technologies for the case studies a small questionnaire was circulated among the CIKC technology and advisory board members and technology project investigators. The questionnaire asked participants to nominate technologies they considered to be breakthrough technologies in two time periods; 1950-1980, and 1980 onwards. The questionnaire yielded 17 technologies (with multiple participants selecting the same technologies).

Case study selection
This list of 17 technologies was further refined down to the 7 technologies selected for the project. The refinements were made using the count of technologies nominated (whether multiple people nominated the same technology), spread of technologies across the two time periods (responses were dominated by technologies in the early time period) and then desk based research to identify a coherent group of technologies for analysis. We recognise this case selection method favours technologies in the materials sciences and physics fields because of the interests and expertise of the scientists and researchers we asked to nominate cases. However, the selection method allowed us to work on a group of cases with some technical coherence and also relationship with the current technological work of the CIKC. It also allows us to talk with more depth about the specific materials science commercialisation process. Individual case studies of the seven selected technologies is presented is available on request.

Case study analysis
The case study analysis is divided into three sections, a section for each of the three phases of breakthrough technology development; science base, pre-commercial environment and commercial environment. The science base is primarily concerned with discovery, the pre-commercial environment with the activities around establishing the potential of the technology, and the commercial environment on executing on this potential. These three phases cannot be seen as rigid categories as elements of each of these phases is present in the other; the process of discovery is ongoing in all of the phases, and establishing the reputation and potential of a technology occurs in both the pre-commercial and commercial environments. The characteristics discussed in the following sections are highlighted because they are dominant in their particular commercialisation phase.

<u>Science base</u>
Cumulative nature of scientific knowledge
Firstly, the cumulative nature of scientific knowledge development is evident in the initial stages of breakthrough technologies analysed in the case studies. All of these breakthrough technologies could trace their lineage back many years, often centuries to scientific advances developed long before. Liquid crystals were discovered in 1888, the photovoltaic effect was discovered in 1839 and the magnetoresistance effect (behind giant magnetoresistance) and the peizoresistive effect in metals (basis for MEMS) go back to Lord Kelvin (William Thomson) in 1850s.

Multidisciplinary research and co-located researchers
The breakthrough technologies analysed in the cases emerged through the contact of different disciplines in the form of multi-disciplinary research teams, or contacts between scientists of different disciplines within large R&D labs, or through specialised conferences. The effects of multidisciplinarity was evident both in the creation of formal multidisciplinary teams on specific research projects, but also through chance informal contacts between colleagues of different fields co-located within the same institutions.

Interdisciplinary research was considered a new concept. Until the early 1950s R&D had usually progressed through fields of research, rather than interdisciplinary teams. The Manhattan project (US effort to develop and build the first nuclear weapons during the second world war) has been referred to as "the first time that physicists, chemists and engineers worked together for a common goal" (Castellano 2005 p.9). Multidisciplinary research was not necessarily a goal of organisations involved in science based commercialisation, but rather a result of problem-based research agendas.

All the technologies analysed for this research benefited from this inter-disciplinarity. In LCD the interactivity between organic chemists, physicists and electrical engineering led to the creation of displays; in fibre optics it was the interplay between optics, physics, electronics and speciality glass fabrication that lead to the development of fibre optic communications. In the development of photovoltaics Daryl Chapin of Bell labs was initially trying to create dry cell batteries using selenium. He discussed the problem with his friend and colleague at Bell, Gerald Pearson (who was working on solid state silicon devices), who in turn discussed the problem with his colleague chemist Calvin Fuller. Fuller suggested that the problem may be overcome by using silicon doped with gallium in a hot lithium bath would produce more effective electricity generation. These discussions led to experiments and the development of a prototype which in 1952, was the most efficient solar cell, five times more efficient in solar to electricity conversion than anything that had been developed before (Perlin 2004).

The industrial research and development of the US in the post WWII period was a watermark period in the history of micro electronics – during this period the silicon chip was created along with a host of other micro-electronic development that were the predecessors of many technologies that are ubiquitous to us today. The major labs were AT&Ts Bell labs ("undisputedly top of the ladder"(Johnstone 1999), RCA's Sarnoff Centre, and the R&D labs of major corporates such as Westinghouse, GE, Texas Instruments and International Business Machines (IBM).

Similar corporate laboratories existed in Europe, Standard Telecommunications Labs (STL) and GTE Laboratories in the UK, Thompson CSF (France), Hoffman La Roche (Switzerland), and Siemens Aktiengesellschaft (Germany), and Sharp Corporation, Canon, NEC and Fujitsu in Japan. National research laboratories also played a part. These laboratories were usually linked to national military, energy or space departments (for example, Department of Defence and NASA in the US, Royal Signals and Radar Establishment (RSRE) in the UK, Commissariat a L'Energie Atomique in France).

Despite the much heralded decline in corporate R&D programs globally and the shift to 'open' innovation sourcing (which sees major corporates look externally to universities and SMEs for innovations rather than developing all innovations in-house (Chesbrough 2003)), in the case of GMR, the most recent breakthrough technology case study, corporate labs (IBM in this case) still played a pivotal role in engineering and developing the newly discovered giant magnetoresistance effect[2]. The post WWII era of investment in science and technology by both firms and governments; the military-industrial-university complex (Hughes 1998), exhibited most definitively by the US in the 1950s and 1960s, has no doubt generated many more technological advances than would otherwise have occurred. Whether the current systems of military-industrial-university complex can maintain the flow of technological advances is unknown, the long timelines involved means we will need to wait a few more decades.

Blue skies research – space for curiosity driven research and ideas

[2] Giant Magnetoresistance (GMR) was discovered in 1988, by two groups of researchers, one led by Peter Grunberg of Forschungszentrum in Julich Germany, and the other led by Albert Fert of Universite Paris-Sud in France. The two groups were working independently of each other and made the discovery of a fall in electrical resistance when a magnetic field was applied to thin, multilayered metal structures. Grunberg and Fert shared the Nobel Prize for Physics in 2007.

Many of these breakthrough technologies analysed in the cases emerged out of programs that can largely be considered 'blue skies' research. Resources, including people and investment were committed to try and understand a certain field of potential application, such as RCA's focus on developing the 'TV on the wall'. Liquid crystals was only one of a number of potential display technologies that RCA was investigating for their goal of a 'TV on the wall'; light emitting diodes, electrolumiscence and plasma materials were other display materials also being explored.

When many of the initial ideas and concepts underlying these breakthrough technologies were first suggested they were considered very radical and not, at first, the logical path of the development of the science base. For example when the potential of optical fibres as a communication medium was first mooted by Alec Reeves of STL in the UK in the early 1960s, he suggested that microwave frequencies (which was the technology in pre-commercial development at that time and expected to succeed radio frequencies) be skipped altogether and attention be focused on optical frequencies, even though at the time the gap between the transmission rate of the two was a factor of 100,000 in favour of microwave transmission (Hecht 2004).

Key discoveries that led to breakthroughs in the cumulative history of these technologies were also disproportionately made by young researchers (such as Nick Holonyak from GE who discovered red LEDs in 1962, and Lawrence Curtiss of the University of Michigan, who developed the glass cladding method for optical fibres that achieved low-loss levels). At the time of making their discoveries these researchers had less credibility and reputation within their organisations than more senior and established researchers and had to battle very hard to get the technology taken seriously. This also links in with the role of technology champions, discussed in further detail in a following section. Technology champions were people who did have status, power and reputation within the system and could support these 'radical' ideas.

Threats from the business cycle

Due to the tentative and speculative nature of this blue sky interdisciplinary research and the inability at the early stage to link the programs with ongoing or even medium term revenue streams, these programs were particularly susceptible to movements in the business cycle. The case studies provide many examples of research programs being abandoned just prior to a breakthrough (that was subsequently developed by another organisation) or, more commonly, abandoned in the pre-commercial phase of its development[3], so the basic science is complete but further development work needs to be completed and resources invested to achieve full commercial reality. Of course these realisations are made only with the passing of time and the benefit of hindsight, but the case studies to provide examples of times when firms have chosen not to cut pre-commercial R&D programs during difficult economic times and have ultimately benefitted in the long run.

The wider macroeconomic environment, particularly commodity prices (oil), and the regulatory environment also were significant drivers of activity in a number of the breakthrough technologies. The most obvious example of commodity prices on breakthrough technology is in the photovoltaics case study and the involvement of oil companies in the development of terrestrial photovoltaic technology. US government regulations on stop-light signals for motor vehicles were also a driver for LED technology and market development. Vehicle safety regulations have also driven the integration of MEMS sensor applications in airbag and anti-lock breaking systems.

The role of technology champions

[3]Examples include; RCA withdrawing from the development of LCDs; ICI withdrawing from the development of industrial inkjet printing which was subsequently developed by CCL and spin out firm Domino; Monsanto and Texas Instruments withdrawing from further development of LEDs due to presumed inability to compete with forthcoming Japanese LED development.

In each of these research case studies there are a small number of people that were instrumental in moving a technology from the science base into commercialisation. These pioneers as they are often called are able to recognise the value of the technology from very early on, and envisage the ways in which the new breakthrough will (to a limited extent – as there are many quotes from these people about how the progress of a certain technology progressed even beyond their imaginings) change the industrial landscape and create new markets and applications.

These people usually have authority and status within the science system, so therefore can be taken somewhat seriously (as most of the ideas are very left field when they first emerge). The technology champions also have the ability to communicate the value of the breakthrough to non-scientific people – i.e. senior management, marketing departments and government representatives and policy makers. This is especially important in trying to access further resources – people and money, to progress a technology through commercialisation.

Luck
The random element of luck can also not be discounted as a factor in breakthrough technology emergence, although the saying, that 'luck favours the prepared' is also apt, because although a researcher may get lucky, in order to fully capture and capitalise on that luck they need to be able to achieve all the other things mentioned above. It is important to mention luck because it emphasises the unknown quantity in scientific development and how we cannot be too formulaic in approaching investing resources in these activities.

<u>Pre-commercial environment</u>
There are a number of factors, which the cases have shown as being important in moving a science discovery out of the lab and into the market. These include focused R&D programs; usually government sponsored but also requiring elements of private investment as well. These R&D programs operate either directly as grants, or as government contracts for R&D services and prototype products. These government programs also usually include the provision of access to specialist testing equipment and the creation of standards, and finally the provision of early, and non-price sensitive customers, such as the military.

Small niche applications for non-price sensitive customers
The case studies highlight a key step for a technology to move from science base to pre-commercial environment are the presence of small niche applications for customers who will tolerate the technology is a less refined and cruder form. This phase is necessary to give the pre-commercial environment focus (otherwise referred to as a mission-driven environment), because up until this point (although there may be some overlap) the process has been about discovery and invention. The mission driven focus of the pre-commercial environment does not end the process of discovery and invention completely, but shifts the focus from exploration to exploitation.

Complementary developments
The path of a breakthrough technology is not solely dependent on the success or failure of the technology alone, but also the success of other complementary and competing technologies that are also being developed. LCD was not the only flat panel display technology under development in the later part of the twentieth century. Other display technologies included plasma and light emitting diodes (LEDs). The plasma flat panel display TV were the first to be commercially successful, only to be quickly followed by LCD displays (which had advantages in materials survival and cost reductions through economies of scale), which are now in turn facing competition from LED (organic or OLED) flat screen displays (although OLEDs have advantages in reduced power consumption and brighter contrast they have not achieve costs reductions through economies of scale yet).

The case studies highlighted multiple examples of where the case study technology found a pathway forward into the pre-commercial and commercial environment through the advance of another technology. The most obvious example is lasers and the use of fibre optics as a communication medium.

Corporate strategy towards commercial environment

This section provides some analysis of the strategic decision making of organisations involved in transitioning breakthrough technology from the pre-commercial environment into the commercial environment. Activities discussed will necessarily span both the commercial and pre-commercial environment but primarily involve commercial actors in the form of firms.

Corporate strategy is a key factor in understanding the direction that such science based technology commercialisation takes. In the absence of a known market and applications with functions and advantages not necessarily known or appreciated by customers, organisations must have other strategic reasons for pursuing technology development other than market demand.

This section examines four areas of corporate strategy in further detail. Strategy in regards to market position (including strategy to potentially cannibalise a firm's existing market with new technology), strategy in regards to accessing new technology (internally and externally), strategy in terms of the vehicle of commercialisation used (start-up, spin-out or corporate unit) and finally strategy in terms of funding technology development (government grants, R&D contracts, alternative revenue streams etc).

Market position

Breakthrough technology commercialises into an environment with little, if any, market feedback. The decision to enter a market with a new application based on breakthrough technology is based on reasons aside from current market demand. These reasons include the belief of the firm, or key individuals within the firm, that a new application will result in a significant market opportunity. These individuals (more than product champions, but similar to technology champions) include people like 'Dr Rocket' at Sharp.

Other reasons include strategic supply and diversification. Monsanto became involved in the development of light emitting diodes because of their access to phosphorous. Oil companies became involved in the development of photovoltaics through mergers and acquisition activity during the oil crisis of the 1970s and as a result of having profits available for investment and a concern in maintaining energy supply and security.

Knowledge sourcing

Another area of corporate strategy is the decision making involved to either bring in new knowledge or to develop in-house capability in regards to a technology. In all of the cases studies two types of broad technological capability were visible; capability around discovery and capability around developing and manufacturing applications. Many firms, particularly in the US in the 1960s period had capability in a number of fields of discovery, however in capability of developing applications and manufacturing applications there were fewer.

In the LCD case, Sharp acquired technology licenses for the dynamic scattering mode LCD from RCA and then invested heavily (US$200m+) to develop a manufacturing capability in LCD. RCA had many resources to draw on for the scientific development yet could not afford or justify the full manufacturing of displays. This was primarily because they did not want to cannibalise their existing and highly profitable CRT market. Consequently, RCA refused to take a long term and product position in the LCD market despite doing a lot of the original research.

Corning provides another example of knowledge sourcing strategy. Corning decided to extend their knowledge of manufacturing to create capability in discovery as well. At the time of the early days of fibre optics development, Corning was a medium sized glass manufacturer in upstate NY. They did not have the resources to compete in R&D against Bell Labs in the telecommunications market yet they saw optical fibres as a way to expand capacity and possibly exploit their know-how in the use of speciality fused silica[4].

To support the R&D program Corning contacted a group of cable manufacturers; their logic was that target customers were current telecommunications cable providers, if optical fibres were to emerge as the next generation fibre, they would still need to be produced as cables. A group of five international cable manufacturers including Pirelli in Italy, Siemens in Germany and BICC in the UK agreed to support the program via the payment of an annual fee. This payment did not entitle any of the cable manufacturers to any IP relating to the R&D project, but entitled them to be kept up to date with progress and have first rights to license and buy any resulting cables. Corning's decision to expand their technical capability in glass manufacturing by supporting it with a base in basic optical fibre research allowed Corning to develop and ultimately profit from the optical fibre revolution.

The Inkjet printing case study provides a further example of knowledge sourcing strategy, but in this case in the opposite direction. CCL had completed much of the basic research around developing a new method of industrial inkjet printing under a contract for the chemicals firm ICI. ICI decided not to pursue the research and allowed CCL to retain the intellectual rights to the work they had contracted them to do. CCL developed this research over a number of years before creating a spin-out company to fully resource and develop a manufacturing capability for the technology. The resulting spin-out company was named Domino.

The previous three examples have highlighted three methods of how knowledge sourcing happens in this pre-commercial environment

1. Bringing in new knowledge then investing to create internal capability in both discovery and development.
2. Building on existing commercial and manufacturing capability drawing in resources to develop a discovery capability that can drive a future direction of development.
3. Building on an existing capability for discovery and adding resources – in this case through a spin-out company, to develop the technology.

Commercialisation vehicle

Another area of strategy in the pre-commercial area of development relates to the commercialisation vehicle – by this we mean the vehicle in which the technology is incubated in the pre-commercial stage. Examples include start-up, spin-outs and corporate units. We have already seen examples of spin outs (Domino from CCL) and corporate units (Sharp and Corning). In the case study technologies the majority of pre-commercial development is incubated in a corporate and then to a lesser extent spin-out vehicles. This is no doubt a factor of the development stage of the technology – as the technology develops and uncertainty surrounding it decreases, we see more spin-out and then start-up activity.

Start-up activity appears to be much less than expected of radical industrial development. This is probably a result of the technologies selected, and their concentration in physics based sciences with high barriers of entry (due to equipment and materials needed) than in other technology sectors. There are only a few examples of start-up activity in the early days of a technology. Start-up activity increases as technological uncertainty decreases. E.g. LCD – handful of start-ups founded by early pioneers of the technology, had limited success and

[4] Silica was more difficult to work with than traditional glass. Traditional glass melts and can be pulled into fibres at between 1200-1500 degrees, silica needs temperatures well over 2000 degrees to even soften. Silica also has the lowest refractive index of any glass (Bell 1988).

lasted only a few years. One example of a start-up in the early days of a technology is NVE Corp, which has a specific application development strategy that supports R&D activity in main area of pre-commercial interest, MRAM.

Funding
The final area of corporate strategy analyzed across all of the case studies relates to financing of the pre-commercial stage. In this report there have already been cited numerous examples of how organizations supported the development of pre-commercial technology, including accessing government R&D programs and R&D contracts, funding new areas of technology development through existing revenue, and gathering external funding support from customers (such as in the example of Corning and the group of cable providers that supported Corning's initial optical fibre research program). In this section details of these funding support mechanisms and their effects on technology development are discussed.

Government R&D contracts
Government R&D contracts were an important source of pre-commercial technology development in all of the cases analyzed. In the LCD case R&D contracts were for military applications in display devices (mainly for aircraft cockpit displays). In fibre optics development government contracts were frequent as a result of the telecommunications function still being under government control and/or government monopolies in most countries. There was however other R&D contracts for the development of solutions for military use (such as ship communication systems). Photovoltaics early development was largely funded by the space program in the US and the need for remote power applications in other countries (remote telecommunications in Australia, and coastal lighthouses in Japan). In the more recent case of GMR development government (US military) contracts supported the development of magnetic sensors for land mine detectors. In each of the government contracts the activities supported are pre-commercial technology development generally, and for development of specific niche, high cost, low volume applications primarily for military use. The use of these contracts varies greatly between countries. The US has the most prevalent activity in these types of contracts.

Government R&D and other programs
Many other governments support technology through specific R&D programs which are aimed at pre-commercial support in technology and market development around a group of applications. These programs provide not only R&D support and subsidies for specific areas of breakthrough technology development, they also provide access to specialized equipment, forums for the establishment of standards, and in some cases direct financial support for establishing new industries. Public procurement also provides another mechanism for government to support breakthrough technology in the pre-commercial environment. The cases highlight examples of governments procuring R&D but also, and in many cases more critically acting as deep-pocketed first customers and procuring first quantities of technologies. Government customers include military, health and energy departments.

Corporate funding
Corporate funding from internal revenues is the other significant funding source for pre-commercial breakthrough technology support. With the acknowledgement that much of the breakthrough technology analyzed in these case studies emerged from corporates, also comes the acknowledgement that by and large these breakthrough technologies emerged from large firms as opposed to small ones. This may suggest that in the case of science-based technologies successful commercialisation favors larger firms, or has done so in the past.

Other funding mechanisms
In a number of the case studies, novel funding mechanisms, what we have described as 'money clubs' existed to support pre-commercial breakthrough technology development. Corning used funding from a group of international cable providers (their potential customers

for any new form of optical fibres) to support their earlier research on single mode optical fibres. Elmjet, one of the later spin out firms from Cambridge Consultants, developing binary deflection continuous inkjet technology created a User Council. Potential customers were invited to join this user council with an annual membership fee of £50,000. Six firms were invited to join the user council and they were from different market segments and not in direct competition with each other. For their membership these six companies had access to information on how the technology was developing and priority ordering for any emergent product.

Absence of Venture Capital
The technologies investigated in the case studies highlighted few examples of the use of venture capital funding to support technology and market development. This should not be a surprising result given the breakthrough nature of the technologies examined. Venture capital is a source of funding for a limited number of firms with very specific characteristics in terms of technology development and market opportunity. Firms that seek equity investments are typically small firms rich in intangible assets such as technology and specialist knowledge but lacking in other forms of assets that provide the means to access other forms of external finance such as debt finance. Venture capital funds are typically looking to invest in firms that have a great opportunity for extra-ordinary profits and the ability to make a return on investment (equity share returned back to the fund in form of cash) within ten years. As a result venture capital funds would look to invest only in technology applications that were in the commercial environment.

In examining the long periods of time these breakthrough technologies spend in the pre-commercial environment the limited activity of venture capital in these breakthrough technologies is not surprising. This is not to say that venture capital is unimportant in commercializing technology. If the cases examined further the successive waves of innovation and application development of these breakthrough technologies when they are established in the commercial environment, venture capital financing would feature regularly. Issues with the availability of venture capital in this environment for new technology based firms are well known[5] as to activities by governments aimed at increasing the supply of venture capital finance (OECD 2006). Government activities aimed at increasing the supply of venture capital finance to new technology based firms can only play a specific and limited role in the commercialisation of science-based breakthrough technology. This is because venture financing is a suitable means of funding technology development for a specific set of firms operating at the end of the overall commercialisation cycle that we have examined in these cases.

Conclusions
This research set out to address two questions.
1. How do commercialisation patterns emerge for breakthrough technologies?
2. What are the key factors/ inflection points in these commercialisation patterns for breakthrough technologies - both successful and unsuccessful commercialisations?
How do commercialisation patterns emerge for breakthrough technologies?
The commercialisation patterns of breakthrough technologies are best illustrated by what Adner and Levinthal (2002) refer to as speciation events. In that progress is cumulative and slow up to a certain point of discovery or breakthrough, and then dramatic and quick evolutionary change takes place and new technology with new potential applications, markets and industrial direction, emerges.

The evolutionary approach highlights three further characteristics of breakthrough technology commercialisation; the process involves long time lines; successful breakthrough

[5] Please see Sharpe, Cosh et al (2009b) and the CIKC/ NESTA crossover report for this project Sharpe, Cosh et al (2009a) for further details on these issues.

technologies are comparatively rare events; and breakthrough technologies have the ability to cause dramatic changes in the industrial landscape.

This report has illustrated three phases of commercialisation; the science base, the pre-commercial environment and the commercial environment. In each of these phases certain activities and characteristics dominate; in the science base, activities of discovery; in the pre-commercial environment activities of establishing potential and reputation of technology; and finally the commercial environment is dominated with executing on this established potential. Although these activities are associated with different phases, they do not exclusively exist only in these respective phases, discovery activities continue in all phases for example.
Studying the activities dominating the different phases allows us to differentiate the phases and give adequate explanation and analysis to the actors and the decisions they make in context. Citing people at the centre of the analysis also emphasises the importance of people; these are case studies are about people, their interactions, movements, decisions and achievements.

What are the key factors in these commercialisation patterns?
Throughout this report we have identified two transition periods in the commercialisation of science-based technology; the transition from science-base to pre-commercial environment, and the transition from pre-commercial to commercial environment.

A number of factors in each transition have been identified and are summarised in figure 5. Factors that drive technology from the science base to the pre-commercial environment include interdisciplinary interaction, time, a background of blue skies research activity that is sheltered from the business cycle, technology champions that spread the word of the potential applications and establish direction for the new technology, and finally, luck. Luck that the right people will meet at the right time and that certain research will be supported at the right time.

Factors that see a breakthrough technology transfer from the pre-commercial environment into the commercial environment include the development of niche applications and/ and for non-price sensitive customers. These early applications build the reputation of the new technology.

Another key factor is corporate strategy in regards to a new technology and the resources that firms (primarily large firms) invest in the development of this technology. Strategic areas include;

- Whether or not to pursue a market and product position with a new technology,
- Whether to extend their field of knowledge in regard to a new technology and how this is achieved (developing internal knowledge capacity or bringing in external knowledge in the form of technology licensing)
- Whether to cannibalise existing products/ markets with new technology
- Vehicle of commercialisation – start-up, spin out or corporate unit
- How to support pre-commercial development; through pursuit of R&D contracts, participation in R&D programs (usually cooperative), internal revenue or external sources such as ‘money clubs’ and risk capital.

References

ABC (2004) The Australian Photovoltaic Industry Roadmap, Australian Business Council for Sustainable Energy.

Abernathy, W. J. and K. B. Clark (1985) "Innovation: Mapping the Winds of Creative Destruction." *Research Policy* 14: 3-22.

Adner, R. and D. A. Levinthal (2002) "The Emergence of Emerging Technologies." *California Management Review* 45(Fall): 50-66.

Asakawa, K. (2007) Metanational Learning in Tft-Lcd Industry: An Organizing Framework. *RIETA Discussion Paper Series* Japan, Research Institute of Economy, Trade and Industry

Bailey, S. G., R. Raffaelle and K. Emery (2002) "Space and Terrestrial Photovoltaics: Synergy and Diversity" *Progress in Photovoltaics: Research and Application* 10: 399-406.

Bell, T. E. (1988) "Fiber Optics" *IEEE Spectrum* 25th Anniversary special edition: 97-102.

Businesswire (2002) "NVE announces technology exchange with Cypress Semiconductor; Companies to share technology; Cypress to invest over $6 million", *Business Wire*, 24th April 2002

Businesswire (2004) "NVE Corporation provides MRAM update", *Business Wire*, 19th March 2004

Carey, J. (1994) Science and Technology for Risky R&D, a Sweetener from Uncle Sam. *Business Week*: 84.

Castellano, J. (2005) *Liquid Gold: The Story of of Lcds and the Creation of an Industry*. New York, World Scientific

Chandler, A. D. (2001) *Inventing the Electronic Century*. New York, The Free Press.

Chesbrough, H. (2003) *Open Innovation: The New Imperative for Creating and Profiting from Technology*. Boston, MA, Harvard Business School Press

Christensen, C. M., M. W. Johnson and D. K. Rigby (2002) "Foundations for Growth - How to Identify and Build Disruptive New Businesses" *MIT Sloan Management Review* 43(3): 22-31.

Connell, D. (2006) *'Secrets' of the World's Largest Seed Capital Fund: How the Us Government Uses Its Small Business Innovation Research (Sbir) Programme Budgets to Support Small Technology Firms*. Cambridge, Centre for Business Research, Cambridge University.

Ettlie, J. E., W. P. Bridges and R. D. O'keefe (1984) "Organization Strategy and Structural Differences for Radical Innovation Versus Incremental Innovation" *Management Science* 30(6): 682-695.

Freeman, C. and L. Soete (1997) *The Economics of Industrial Innovation*. London, Continuum

Fyfe, M. (2003) "Has the Sun Set on Solar Power" *The Age*. Melbourne.

Green, M. A. (2007) "Moguls and Entrepreneurs" *Time*. Shi Zhengrong.

Grover, V., R. L. Purvis and A. H. Segars (2007) "Exploring Ambidextrous Innovation Tendencies in the Adoption of Telecommunications Technologies" *IEEE Transactions on Engineering Management* 54(2): 268-285.

Hart, S. L. (1983) "The Federal Photovoltaics Utilization Program: An Evaluation and Learning Framework." *Policy Sciences* 15: 325-243.

Hecht, J. (2004) *City of Light: The Story of Fibre Optics* New York, Oxford University Press.

Hu, M.-C. (2008) "Knowledge Flows and Innovation Capability: The Patenting Trajectory of Taiwan's Thin Film Transistor-Liquid Crystal Display Industry." *Technological Forecasting and Social Change* 75: 1423-1438.

Hughes, T. (1998) *Rescuing Prometheus* New York, Pantheon.

Johnstone, B. (1999) *We Were Burning: Japanese Entrepreneurs and the Forging of the Electronic Age* New York, Basic Books.

Jutiagroup.com (2009) "Nanotech stocks profiting from spintronics: will NVE Corp live up to the hype", *http://jutiagroup.com/2009/05/05/nanotech-stocks-profiting-from-spintronics-with-nve-corp-nvec/*, accessed 8th September 2009

Kassicieh, S., B. A. Kirchhoff, S. T. Walsh and P. J. Mcwhorter (2002) "The Role of Small Firms in the Transfer of Disruptive Technologies" *Technovation* 22: 667-674.

Kassicieh, S., S. T. Walsh, A. Romig, J. Cummings, P. J. Mcwhorter and D. Williams (2000) "A Model for Technology Assessment and Commercialisation for Innovative Disruptive Technologies" *IEEE Spectrum*: 340-344.

Kressel, H. and T. V. Lento (2007) *Competing for the Future: How Digital Innovations Are Changing the World* New York, Cambridge University Press.

Linden, G., J. A. Hart, S. A. Lenway and T. P. Murtha (1998) "Flying Geese as Moving Targets: Are Korea and Taiwan Catching up with Japan in Advanced Displays?" *Industry and Innovation* 5(1): 11-34.

Linton, J. D. (2009) "De-Babelizing the Language of Innovation" *Technovation* 29: 729-737.

Maine, E. and E. Garnsey (2006) "Commercializing Generic Technology: The Case of Advanced Materials Ventures" *Research Policy* 35: 375-393.

Mathews, J. A. (2005) "Strategy and Th Crystal Cycle" *California Management Review* 47(2): 6-32.

McCray, W. P. (2009) "From Lab to Ipod: A Story of Discovery and Commercialisation in the Post-Cold War Era" *Technology and Culture* 50: 58-81.

Minshall, T., S. Seldon and D. Probert (2007) "Commercializing a Disruptive Technology Based Upon University IP through Open Innovation: A Case Study of Cambridge Display Technology" *International Journal of Innovation and Technology Management* 4(3): 225-239.
Nelson, R. R. (1990) "U.S. Technological Leadership: Where Did It Come from and Where Did It Go?" *Research Policy* 19: 117-132.
Nemet, G. F. (2009) "Demand-Pull, Technology-Push, and Government-Led Incentives for Non-Incremental Technical Change" *Research Policy*.
Nrc (1999) *Funding a Revolution: Government Support for Computing Research* Washington, Computer Science and Telecommunications Board, National Research Council.
NVE (2009) "NVE Corporation Reports Fourth Quarter and Fiscal Year Results", *NVE press release*, http://www.globenewswire.com/newsroom/news.html?d=164604, accessed 8th September 2009
Nanotechwire.com (2006) "NVE Corp. Spins Electrons into Profits", *Nanotechwire.com*, http://www.nanotechnology.com/blogs/steveedwards/2006/03/nve-corp-spins-electrons-into-profits.html, accessed 8th September 2009.
Pacific Solar (1998) *Annual Review* 1998
Pacific Solar (1999) *Annual Review* 1999
Pacific Solar (2000) *Annual Review* 2000
Pacific Solar (2001) *Annual Review* 2001
Pacific Solar (2002) *Annual Review* 2002
Pacific Solar (2008) *Annual Review* 2008
Pavitt, K. (1991) "What Makes Basic Research Economically Useful?" *Research Policy* 20: 109-119.
Perlin, J. (2002) *From Space to Earth: The Story of Solar Electricity*. Cambridge MA, Harvard University Press.
Perlin, J. (2004) "The Silicon Solar Cell Turns 50" *National Renewable Energy Laboratory Report*. Wsahington, National Centre for Photovoltaics.
Sharpe, S., A. Cosh and D. Connell (2009a) Summary Report of the Nesta Project for the Cikc Gunding Breakthrough Technology Project. Cambridge, Centre for Business Research.
Sharpe, S., A. Cosh, D. Connell and H. Parnell (2009b) *The Role of Micro Funds in the Financing of New Technology Firms*. London, NESTA (National Endowment for Science, Technology and the Arts.
Sklar, S. (1990) "The Role of the Federal Government in the Commercialisation of Renewable Energy Technologies" *Annu. Rev. Energy* 15: 121-132.
Tijssen, R. J. W. (2002) "Science Dependence of Technologies: Evidence from Inventions and Their Inventors" *Research Policy* 31: 509-526.
Tosh, J. (1984) *The Pursuit of History* Harlow, Essex, UK, Longman.
Utterback, J. M. (1996) *Mastering the Dynamics of Innovation*. Boston, Mass., Harvard Business School.
Watt, M. (2003) "The Commercialisation of Photovoltaics Research in Australia" - *A Report for Science and Innovation Mapping*, Department of Education, Science and Training, University of NSW.
Welles, E. O. (1998) "Going for Broke" *Inc.*
Wessner, C. W. (2001) *The Advanced Technology Program: Assessing Outcomes*. Washington DC, National Research Council (US), Board of Science, Technology and Economic Policy.