Consistent National Policies for Converging Technologies: Some Preliminary Conclusions

Policy Report of the CSES Project General Purpose Technologies, Complementarities and the Convergence of Industries

Australian Research Council
ARC Linkage Grant Project ID: LP0349387

November 2006

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Acknowledgements
The authors gratefully acknowledge funding from the Australian Research Council under a Linkage Grant (LP0349387) and the support of the Industry Partners to that Grant (the Department of Industry, Tourism and Resources, the Department of Innovation, Industry and Regional Development (VIC), IBM Australia Ltd, Starpharma Ltd and AusBiotech Ltd). None of these partners are in any way committed to the views expressed here.

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Executive Summary

It has become common to refer to technologies that meet three conditions – pervasive effects throughout the economy, room for further development and complementarities with other technologies – as general purpose technologies (GPTs). Historical examples have been the steam engine and electricity, and currently information and communications technologies are fulfilling this role. We are in the early stages of a process of convergence at the nano scale of three major streams – information technology, biotechnology and nanotechnology – here referred to as the converging technologies (CTs). This process of convergence will give rise to a suite of new GPTs, which will have major implications for science and for economic and social life. This fact gives rise to the policy issues addressed in this paper.

Theoretical Frameworks for Policy Analysis

Two theoretical frameworks are employed in this analysis. In respect of the impact of GPTs on long run growth, the literature stresses their impact on the development of other technologies (hence driving the process of convergence itself) and, particularly, the large scale investment in intangible assets that they necessitate. Adapting to a GPT requires heavy investment in each of the four elements of intangible capital – human, organisational, marketing and production technology capital. The need for this investment helps to explain why the productivity impact of a new GPT is often delayed, but also why the growth impact is so large in the long run.

In terms of innovation at the firm level, we employ a framework that integrates the resource based view of the firm with the more recent approach of open innovation. In this framework three matters emerge as central to effective innovation at the firm level: the development and protection of strategic assets, integration into networks and alliances to assist in developing and applying those strategic assets, and the critical importance of the business model used. Thus our overall framework emphasises intangible capital/strategic assets at both the aggregate and firm levels, and networks and alliances and a viable business model at the organisational level.

Key Characteristics of Converging Technologies

Six characteristics of the CTs are most relevant for Australian policy at this time.

- *Pervasiveness*: As noted, the converging technologies are likely to give rise to a suite of GPTs, and hence to have pervasive effects throughout industry, the service sector and social life. Advanced capabilities in these areas will be vital for national competitiveness and prosperity in the medium term.
- *Diversity*: There is great diversity within this suite of technologies, in terms of the requirements, in many dimensions, for their development and application.

- *The growing role of open access*. In many areas, such as open source software or the human genome, open access to new knowledge is becoming common; in other areas, such as medicines, proprietary intellectual property remains vital.
- *Networks and alliances*: The rising cost and complexity of new technology development has led to this becoming a global process, beyond the reach of any single country or company. Complex webs of networks and alliances span the globe: active participation in them is necessary to keep pace with the technological frontier.
- *Role of East Asia and India*: For the first time, the development process for major new technologies involves countries in Asia as foundational players, and large scale investments in these areas are being made in China and India, among others.
- *Variety and fragility of business models*: Given the diversity of technologies and of market conditions, there have been a variety of different business models employed. No single model provides a guarantee of success in changing circumstances, and different models are effective with different technologies and in different regions.

These characteristics have important implications for policy in a small but open and innovative economy. While a strong research base is vital and niche opportunities should be supported, Australia's advantage is likely to be in application areas that have low capital and propriety IP requirements, but can utilise open access information and tacit knowledge to create customised products for markets both in Australia and abroad. Global alliances and linkages are crucial at all stages, and policy should strongly support the building of such alliances, especially with East Asia and India. Finally, it is necessary in framing policy to recognise both the diversity and fragility of business models, and to be flexible in providing support to different models in different circumstances.

Five Principles for National Policy

As a result of these theoretical and empirical considerations, we suggest five principles for policy for converging technologies in Australia.

(*i) Strengthen the Foundations: Tangible and Intangible Capital for Converging Technologies*. The foundations for competitiveness lie in those factors that underpin investment in tangible and intangible capital for these technologies. This covers a wide range: physical or tangible capital, including infrastructure, human capital, R&D and related technological capital, other forms of intangible capital of organisations, including but going beyond firms, and relevant forms of social capital. The latter covers, for example, the willingness of the public to support the adoption of new technologies. Increased investment in some of these areas by governments, and measures to induce such investment by others on a large scale, will be necessary to meet the challenge of the converging technologies.

(ii) Increase Global Integration – Building Networks and Alliances. Deeper integration into global networks and alliances is necessary for competitiveness at all levels of the value chain, from basic research to product marketing. Sustained attention needs to given to ways of supporting this integration, especially in relation to newly emerging research and application centres such as in China and India. A

generalised version of the recently established Indo-Australian Fund for Scientific and Technological Cooperation is one option worthy of further consideration.

(iii) Develop Australia as a Global Centre for CT Applications. Australia can at best be a niche player in basic research and product development in these areas, but it can become a global centre for many applications of the converging technologies. This is beginning to occur in some areas, and should be systematically supported by policy initiatives. Those applications areas that involve low capital cost and can draw heavily on open access technologies, yet address large markets with customised products, would seem particularly appropriate for Australian skills and circumstances. Among the initiatives that should be considered are large scale demonstration projects within Australia and Applications Development Consortia, bring together public and private funding to develop applications for global markets.

(iv) Provide Increased Support across a Range of Different Commercialisation Paths. Australian firms face many barriers to achieving a viable position in global markets, arising from isolation from the main intellectual and business centres and the scale and immaturity of domestic markets. Increased public support to assist them to enter global markets is required, in ways that respect the diversity and fragility of business models.

(v) Coordinate Policies Across Technologies, Applications and Agencies. Given the convergence of technologies and our small scale in the face of intense global competition, it is necessary that national policies be coordinated in several dimensions: across technologies, across application areas and across the national and the state governments.

Conclusion

This paper is a preliminary contribution to the development of an appropriate policy framework for Australia to meet the fundamental challenge of the converging technologies and the general purpose technologies to which they are giving rise. Its intended methodology, incompletely applied at this stage, is to derive the guiding principles for such a policy framework from both a theoretical and empirical analysis of the technologies and the conditions of their application, and of the Australian context, and to examine in detail specific policy proposals to give effect to those principles.

Further work will attempt to base the policy principles on a more rigorous and complete analysis, both theoretical and empirical, than has been possible here, and then to review possible policy options consistent with them in detail.

1. General Purpose and Converging Technologies

1.1 General Purpose Technologies

The literature on general purpose technologies aims to refine the economic analysis of innovation and technological development, based on the premise that all technologies are not the same in their impact on the economy. Some technologies, the so-called GPTs, exercise a much wider impact than others, and the particularity of this influence merits specific examination. This notion of the widespread influence of particular technologies has been long familiar to economic historians, but has gained contemporary attention in the analysis of the impact of information and communications technology (ICT) on current economic development.

The Definition of General Purpose Technologies

The term “general purpose technology” has been extensively used in recent treatments of the role of technology in economic growth. It is usually reserved for changes that transform both household life and the ways in which firms conduct business. Steam, electricity and information technology (IT) are often classified as GPTs for this reason (Jovanovic and Rousseau, 2005). Lipsey, Bekar and Carlaw (1998) argue that a GPT is a technology that initially has much scope for improvement and eventually becomes pervasive (in the sense of being widely used and having many uses) as well as having many technological complementarities. Each of these attributes is a necessary condition for a technology to be a GPT, but the necessary and sufficient condition for overall GPT status is for the technology to possess all of these attributes. That is, a GPT is one that is pervasive in its applications, has further room for improvement and has many complementarities with other technologies.

Pervasiveness can be seen in a wide range of use and a wide variety of uses. A technology’s range of use refers to the proportion of the economy in which the technology is used. The variety of use refers to the distinctive applications for the technology. A GPT can be used in a wide variety of products and processes, which can in turn be used as physical components in main technologies and/or as main technologies within technology systems. The GPT also has a wide range of use in the sense that a significant proportion of the productive activities in the economy use that technology. Pervasiveness is a characteristic that evolves over time. A GPT typically begins as a technology with a limited number of uses and a limited range of use, but evolves into capabilities for a wide variety and range of uses (Lipsey, Bekar and Carlaw, 1998).

The way in which agents learn about technologies, and the complexity of the economy’s overall technology systems, implies that any technology that ends up being widely used in many different applications must go through a process of evolution. Over time, the general purpose technology is improved, its costs of operation in existing uses falls, its value is improved by the invention of technologies that support it, and its range of use widens while the variety of its uses increases. This is true of both the technology of the products themselves and of the processes by which they are made (Lipsey, Bekar and Carlaw, 1998). This process of evolution also means that there is a degree of unpredictability about the emergence of a GPT.

Technological complementarities are of several types. GPTs impact on existing technologies, creating the opportunity, and sometimes the need, to alter many of these. They also create opportunities for profitable investments in a large set of new product, process, and organisational technologies. Complementarities in innovation exist because productivity in research and development in downstream sectors increases as a consequence of innovation in the GPT, as can occur in the opposite process. The ability of the GPT to spawn innovation is most clearly seen with ICT (Jovanovic and Rousseau, 2005).

Technological complementarities occur whenever a technological change in one item of capital requires a redesign or reorganisation of some of the other items that cooperate with it. The effects of this type of complementarity cannot be modelled as the consequences of changes in the prices of factor services found in a simple production function. All of the action is taking place in the structure of capital and the consequent changes will typically take the form of new factors of production, new products, and new production functions. Because GPTs provide inputs that enter into virtually all production, and because they typically lie at the centre of large technology systems, they are vertically and horizontally linked to many other technologies. For this reason innovations in GPTs will typically induce major structural changes in many other technologies.

Examples of General Purpose Technologies

Commercial steam power began to be used in the early 18th century and had its major growth in the 19th century. It became the pervasive energy technology as the predominant source of motive power in manufacturing, while taking a major role in transportation and also being used in agriculture and mining. The improvements that were made in the technology over time were huge, although they took more than a century to achieve. Steam also facilitated technological complementarities in a vast range of capital goods, revolutionary changes in the organisation of industries, and improved transport that helped to encourage the rise of the first globalised economy.

Electricity developed into a GPT in the early 20th century. Electricity powered factories and facilitated the modern consumer economy. It has also powered successive developments in communications technologies, and underpins the contemporary service economy. Successive innovations in electricity generation and transmission technologies have enabled the reach of this technology to become comprehensive. The rate of improvement in the technology of electricity was more rapid than for its predecessor, steam. Electricity has also spawned a vast range of technological and organisational complementarities, including a transformation in the way factory production is organised.

Information and communications technology is the current GPT. ICT is a production technology (chips increase the efficiency of consumer and capital goods and were necessary for the development of computers, the Internet, and smart buildings and factories), process technology (computer-controlled capital equipment in manufacturing and design – CADCAM, and modern supply chain systems), and organisational technologies (new management structures, globalised production systems, increased work out of home).

1.2 Converging Technologies

The convergence of the physical and biological sciences at the atomic level is transforming scientific knowledge, and will continue to do so over the coming decades. The application of this knowledge in technologies at the micro and nano scale will undoubtedly have widespread ramifications throughout industry and society. The impact of these technologies on firms, industries and jobs will be substantial over the next one or two decades. In particular, nanotechnologies – through molecular engineering inspired by biotechnology, electronic technology based on semiconductors, and devices and processes based on new materials – will alter the competitive position of firms and the structure of industries.

These are technologies whose application is not restricted to a single economic sector but whose impact is felt across the whole economy. Each of these technologies is at different various stages of development and importance – ICT is well established with its ramifications across the economy are already evident. The application of biotechnology has been delivering new products in a few well-defined industries. Small-scale technologies, although still in their infancy with a small range of products, are expected to have a broad economic impact.

While these technologies are by themselves capable of having a powerful economic impact, their simultaneous application may have an even greater impact. For instance, the development of genomics is one of a number of advances expected to substantially increase the number of disease targets and therefore the number of drugs available to treat disease. However such was the volume of data produced by the new technology that little could have been achieved without the development of a specialist application of IT, namely bioinformatics. In this case IT has acted as an important enabling technology leading to data management solutions that are expected to produce revolutionary new treatments. Thus the convergence of the two technologies has been particularly powerful.

Many ongoing developments have led to an expectation that the joint application of the technologies would produce even more substantial results than the technologies individually. For instance the convergence of nanotechnology and biotechnology is expected to produce advances in drug delivery and previously unimaginable personalised drug treatments. Nanotechnology is expected to provide a quantum leap in the miniaturisation of communications products.

As previously noted, the evolution of GPTs in inherently uncertain, as a wide range of market and technology developments need to come together for a technology to meet the conditions of being a GPT: pervasive impact across the economy, room for further development and extensive complementarities with other technologies. It is impossible to map with any precision the future development of the converging technologies, and hence to identify emergent GPTs. But the convergence process is so profound that it is reasonable to expect that a suite of GPTs will emerge from it, and this is the premise on which this report has been prepared.

Because of their perceived importance, the commercialisation of the converging technologies has attracted intense interest, not only from the direct participants – companies, entrepreneurs, research organisations and financial institutions – but also from governments. As a result, programs covering the whole spectrum from basic research to commercialisation have been developed and implemented by government agencies in many countries for each of these technologies.

Finally, it needs to be noted that the technologies listed above are broad categories each of which is made up of many component technologies, which may in turn result in a multitude of different applications or products. These specific technology application areas often have important differences in characteristics. The process of convergence is not a process by which many technologies converge into one unified technology at the nano scale. Rather it is a many-many process, and implies a complex sharing and integration of technologies across many different fields, to create a diversity of new technologies. Some of this diversity is explored in Section 3.1 below, and must be kept in mind in developing policy.

2. Theoretical Frameworks and Their Application

In our analysis we draw on two strands of recent theoretical literature concerning these issues, namely that on the ways in which GPTs impact on growth, both in the short term and the longer term, and that on innovation at the firm level. Our central conclusions are summarised below; more details can be found in the project papers, especially Jolley (2006) and Rasmussen (2006a).

2.1 General Purpose Technologies and Growth: The Role of Technological Complementarities and Investment in Intangible Capital

In order to distinguish between the long run and transitional effects of GPTs on the economy, it is necessary to analyse the way in which GPTs interact with other technologies and in which they require complementary investment in forms of intangible capital, such as human capital and business organisation. In the light of the brief discussion of technological complementarities above, we concentrate here on intangible capital.

The Role of Intangible Capital

The research on intangible capital provides a clarification of the means by which GPTs stimulate the growth in productivity. Intangible capital in the form of computerised information provides an important indicator of the wider impact of ICT, the current GPT, on the economy. Intangible capital in the form of R&D provides some indication of the overall rate of technological development in the economy and complementarities between different technologies. Intangible capital in firm-specific resources throws light on complementary investments in human skills and business organisation, key features of the impact of GPTs on productivity.

In their analysis of GPTs, Lipsey, Carlaw and Bekar (2005) stress the importance of the relationship between a GPT and the facilitating structure. The facilitating structure is defined as the set of realisations of technological knowledge, by which is meant the actual physical objects, people, and structures in which technological knowledge is embodied. The facilitating structure encompasses the stock of physical capital, including consumer durables and residential housing; the people and the human capital that resides in them, including tacit knowledge; the physical, managerial and financial management of production; the geographic distribution and concentration of production, including all infrastructure, and all financial, educational, research and governance institutions.

When a new technology is introduced, various elements of the facilitating structure will need to be changed adaptively. Since much time is required to effect these changes, the evolution of the facilitating structure is likely to lag behind the evolution of the technology, particularly when technology is changing in ways that require large adjustments in that structure. Lipsey, Carlaw and Bekar (2005) suggest that GPTs could stimulate the following long-term changes in the facilitating structure:

- a reorganisation of many existing production processes;
- new skills on the part of the labour force;
- new management structures and methods;
- new patterns in the geographical distribution of economic activity;
- new technologically determined scale economies; and
- new economic infrastructure.

In addition, new GPTs may cause permanent changes in the facilitating structure that destroy existing sources of rents and create new ones.

In thinking about the changes that GPTs may require in the facilitating structure it is useful to employ the concept of intangible capital (Webster and Jensen, 2006). Intangible capital consists of all forms of capital not immediately manifest in tangible matter. Enterprise intangible capital is all such capital that exists within the boundaries of the firm: that is, it captures all outlays by firms made in the expectation of future profit other than those for plant, equipment and infrastructure. Ideas, skills and creative potential are the essence of intangible capital. Intangible capital is therefore the embodiment of the knowledge economy.

Many forms of intangible capital that are tacit in nature are not easily encrypted. They may be part of the knowledge held by the workforce or simply be part of the reputation and standing of the firm. Such knowledge can only be shared among those who have the capacity to intuitively grasp the idea. Transmission of tacit knowledge requires context-specific, interpersonal contact and a high degree of understanding between the creator and the recipient. On the other hand, codified knowledge can be more easily transmitted: it does not rely upon interpersonal contact and the level of skill of the user is usually more prosaic.

There are now four well-accepted classes of enterprise intangible capital: human, organisational, marketing (or relational) and production. Human capital arises from investments by the firm or others in the skills and knowledge of its workforce. Organisational capital is represented by the organisational architecture and the systems for monitoring activity and communicating within the firm. Marketing capital comprises control over distribution networks and markets, and production capital is the development and application of new products and processes.

Compared with tangible capital, the production and sale of enterprise intangible capital is dominated by three attributes: production uncertainty, fragmented appropriability, and non-separability. While the creation of tangible capital has developed standards and processes over time so that most items of plant and equipment can be mass produced, the creation of intangible capital is more heterogeneous. It is not clear whether this is because R&D and methods of training have not evolved to a stage of mature mass production, or whether it reflects the inherent difficulty of controlling the quality of services. In particular, the creation of novel intangible capital is uncertain because it arises from situations that are so idiosyncratic that no reliable estimate can be made before the fact.

Appropriating the returns from investment in intangible capital is much harder than it is with tangible capital. The source of the problem is that other parties can copy an idea or concept at minimal cost, meaning the rivals can enter the market and undermine the original inventor’s ability to extract quasi-rents. Nonetheless, this condition does not apply equally to all forms of intangible capital. In some cases, such as technologies that rely on tacit knowledge, the costs of imitation can approximate the costs of invention and appropriability by the creator will be high. Finally, intangible capital is non-separable as investments into workforce training and the organisational architecture of the firm are often not capable of being separated from the original business unit without loss of value.

Empirical Estimates of Intangible Capital for the USA

Published macroeconomic data traditionally exclude most intangible investment from measured GDP. Corrado et al. (2006, also 2004) attempt to rectify this omission by providing estimates of intangible investments and capital in the United States Their estimates suggest that as much as US$800 billion is still excluded from US published data (as of 2003), and that this leads to the exclusion of more than US$3 trillion of business intangible capital stock. To assess the importance of this omission, they add capital to the standard sources-of-growth framework, and find that the inclusion of their list of intangible assets makes a significant difference in the observed patterns of US economic growth. The rate of change of output per worker increases more rapidly when intangibles are counted as capital, and capital deepening becomes the unambiguously dominant source of growth in labour productivity. The role of multifactor productivity is correspondingly diminished, and labour’s income share is found to have decreased significantly over the last fifty years. Table 1 summarises trends identified by Corrado et al. (2006) in business investment in intangibles.

Table 1. Business Investment in Intangibles (US$ billion)

Type	1970-79	1980-89	1990-99	2000-03
Computerised information	4.5	23.2	85.3	172.5
Scientific R&D	34.0	104.6	157.7	230.5
Non-scientific R&D	10.9	58.4	145.2	237.2
Brand equity	18.2	54.4	105.7	160.8
Firm-specific resources	35.7	108.7	255.9	425.1
Estimated total intangibles	103.4	349.3	749.8	1226.2
Tangible fixed investment (NIPA)	171.4	421.1	676.5	893.4
Ratio of intangibles to tangibles	0.60	0.82	1.10	1.36

Source: Corrado et al. (2006).

Computerised information reflects knowledge embedded in computer programs and computerised databases. The former is the dominant element; only in the late 1990s did expenditure on computerised databases become significant, but it was then only 2 percent of the total. Firms capitalise only a fraction of purchased software in financial accounts. Relatively little is known about the service life of software assets.

Scientific and non-scientific R&D reflects not only scientific knowledge embedded in patents, licenses, and general know-how (not patented) but also the innovative and artistic content in commercial copyrights, licences, and designs – "non-scientific R&D". Relatively little is known about non-scientific R&D spending. Information-sector industries – book publishers, motion picture producers, sound recording producers, and broadcasters – as well as financial and other services industries routinely research, develop, and introduce new products. The latter include architectural and engineering designs and the flow-on from R&D in the social sciences and humanities.

Spending on *brand* development is represented by expenditures on advertising (92%) and market research (8%), and encompasses the costs of launching new products, developing customer lists, and maintaining brand equity. Research shows that the effects of some advertising dissipate within one year, but that more than half have effects that last more than one year.

Spending on *firm-specific resources* can be captured by measuring the costs of workforce training and education (29%) and the costs of organisational change and development (71%). Spending on employer-provided training includes both direct firm expenses (outlays on instructors, tuition reimbursements, and the like (19%); and the wage and salary costs of employee time spent in formal and informal training (81%). Investments in organisational change and development have both own-account and purchased components. The own-account component (72%) is represented by the value of executive time spent on improving the effectiveness of business organisations, i.e., the time spent on developing business models and corporate cultures. The purchased component is represented by management consultant fees (28%). This overall category of business investment in intangibles endeavours to capture investments in firm-specific human and structural resources through strategic planning, adaptation, reorganisation, and employee-skill building.

The data in Table 1 indicate that intangible fixed investment has risen sharply in importance relative to tangible fixed investment, from 60% of the level of tangible capital in 1970-79 to 136% of that level by 2000-03. Total business intangible capital is estimated to have increased by 6.9% per annum in the United States between 1995 and 2003.

Implications of Investment in Intangible Capital

The rapid expansion and application of technological knowledge in its many forms (research and development, capital-embodied technical change, human competency, and the associated firm-specific co-investments) is a key feature of recent US economic growth. Accounting practice traditionally excludes the intangibles component of this knowledge capital and, according to the estimates of Corrado et al. (2006), excludes approximately US$1 trillion from conventionally measured non-farm business sector output by the late 1990s and understates the business capital stock by $US3.6 trillion. The current practice also overstates labour's share of income by a significant amount and masks a downward trend in that share.

Their results also suggest that the inclusion of intangibles both as an input and as an output can have a large impact on our understanding of economic growth. They have found that the inclusion of intangible investment in the real output of the non-farm business sector increases the estimated growth rate of output per hour by 10 to 20 percent relative to the baseline case which completely ignores intangibles. Thus, the inclusion of intangibles matters for labour productivity growth rates, although it has little effect on the acceleration of productivity in the 1990s. On the input side, intangibles reached parity with tangible capital as a source of growth after 1995, and when the two are combined, capital deepening supplants multi factor productivity as the principal source of growth. Moreover, the majority of the contribution of intangibles comes from the non-traditional categories of intangibles, such as computerised information, R&D, human and organisational capital.

The research on intangible capital provides a clarification of the means by which GPTs stimulate the growth in productivity. Intangible capital in the form of computerised information provides an important indicator of the wider impact of ICT, the current GPT, on the economy. Intangible capital in the form of R&D provides some indication of the overall rate of technological development in the economy and complementarities between different technologies. Intangible capital in firm-specific resources throws light on complementary investments in human skills and business organisation, key features of the impact of GPTs on productivity.

2.2 An Integrated Approach to Innovation at the Firm Level: Strategic Assets and Open Innovation

The resource based view of the firm, together with the influential ‘core competencies’ concept developed by Prahalad and Hamel (1990), and the ‘open innovation’ paradigm represent two potentially competing approaches to innovation (Christensen, 2006). A strategy based on the resource based view would have a technology intensive company focus on its core technological competencies in order to achieve sustainable competitive advantage. It has been suggested that the adoption of such a strategy would result in an introverted view of innovation in which the firm developed products that were based exclusively on internal R&D (Chesbrough, 2006a). The ‘open innovation’ model suggests that technology companies adopt a networked approach to innovation in which companies and other entities (e.g. universities) exchange ideas and technologies and bring products to market through licensing and other alliance arrangements (Chesbrough et al., 2006). Chesbrough (2003) has argued that the success of an innovation depends on the appropriateness of the business model, a construct to link the technical decisions in the firm to economic value.

In fact the two approaches may not be oppositional to the degree suggested by Christensen (2006) and Chesbrough (2006a), but rather there are complementarities that allow both approaches to be used to better comprehend the innovation process. This section seeks to review the innovation process drawing essentially on three critical concepts from the two approaches: and strategic assets from the resource based view and networks and business models from the open innovation paradigm.

The Resource Based View of the Firm

The resource based view (Wernerfelt, 1984; Barney, 1986, 1991; Dierickx and Cool, 1989; Prahalad and Hamel, 1990; Conner, 1991) places emphasis on a firm establishing a sustainable competitive advantage through the accumulation of strategic assets (Amit and Schoemaker, 1993) that are hard to imitate, substitute or trade. For a technology-based firm its competitive advantage arises from developing, enhancing and exploiting the technologies owned or developed by such companies as strategic assets. Such technology based strategic assets could arise from technological leadership acting as a barrier to entry and so generating economic rents (Wernerfelt, 1984). This might arise from the individual human capital of scientists placing a firm in a unique position to create or exploit a scientific breakthrough which is difficult to imitate (Barney, 1991). In turn this could lead to inter-firm differences in R&D capabilities such as those demonstrated by Henderson and Cockburn (1994) in pharmaceutical research. Since technological leadership can be easily eroded (Dierickx and Cool, 1989) sustainable competitive advantage needs constant investment in R&D (Wernerfelt, 1984).

The lessons to be drawn from the resource based view are several. The first is that firms can achieve a sustainable competitive advantage by virtue of the development of a strategic asset, based on a core competency of a new technology. Secondly, to maintain technological leadership it is important to retain a capability for producing a continuing stream of innovations and constantly to adjust and renew these capabilities in response to rapid technological change. Thirdly, commercialisation of a new technology is possible by a start up where the IP regime provides a sufficiently high level of appropriability to protect the firm against expropriation by potential competitors or partners. A start-up is unlikely to have a full range of complementary assets to complete the commercialisation process, so it will seek partners to provide those it is missing. This leads directly to the open innovation paradigm, where companies supplement their own strategic assets with those of others through network activities.

The Open Innovation Approach

There are two key aspects of the open innovation paradigm of particular relevance to this study. One is the networked nature of the innovation process and the other is the concept of the business model. As Chesbrough (2006a) puts it:

> The open innovation paradigm assumes that firms can and should use external ideas as well as internal ideas, and internal and external paths to market, as they look to advance their technology. …The business model uses both internal and external ideas to create value, while defining internal mechanisms to claim some portion of that value.

The emphasis placed by ‘open innovation’ theorists on the importance of networks and shared knowledge in the innovation process is not new. Networks have a central role in the concept of innovation systems (Freeman, 1987; Lundvall, 1992; Nelson, 1993) and their importance has been highlighted by Arora and Gamberdella (1990), Pisano (1991) and Powell et al. (1996). Typically the more embedded a firm is in the network the more successful it is likely to be as a result of better access to resources and information (Shan *et al.*, 1994; Powell et al., 1999). The central role of technology alliances in the innovation process has been noted by Hagedoorn (1993) and others, in business strategy by Gomes-Casseres (1996) and in the partnership between pharmaceutical companies and dedicated biotechnology companies by Galambos and Sturchio (1998) and Orsengio et al. (2001) among others.

Two concepts are fundamental to helping explain the networked aspect of ‘open innovation’. One is the notion of ‘absorptive capacity’ (Cohen and Levinthal, 1990) and the other is the concept of complementary assets (Teece, 1986). Cohen and Levinthal (1990) defined ‘absorptive capacity’ as the capacity of large firms to take advantage of new technologies. This typically involves the willingness of such firms to invest in basic science in order to better understand new technologies and identify opportunities presented by emerging specialist technology firms. Accordingly (Granstrand et al., 1997) found that companies are becoming more diverse in their technological knowledge platforms, in contrast to the notion of firms sticking to their ‘core competencies’ as proposed by the resource based view. Both IBM and Hitachi represent examples of such behaviour in bioinformatics. IBM with its leading position as a hardware manufacturer and software developer and integrator, saw an opportunity to extend these capabilities to a new domain. As part of the development of its ‘absorptive capacity’ its scientists made a significant contribution to the development of the bioinformatics technology, as evidenced by the number of its bioinformatics patents.

The concept of complementary assets has particular relevance also, as again illustrated by the case of bioinformatics. As predicted by Teece (1986) co-specialised assets often acquired through alliances and other technology licensing arrangements proved to be important for the success of pioneer bioinformatics companies. These companies resorted to both exclusive and non-exclusive external licensing of IP in order to access a broader IP base than that developed internally. Start ups such as Affymetrix blended their expertise in bioinformatics with that of genomics and relied on others with expertise in scientific instrumentation such as Agilent to develop its ‘gene chip’ product (Rasmussen, 2006a).

The recent development of the model of open innovation reflects the perception that the innovation process has evolved from one dominated by large multi divisional, vertically integrated firms, to one in which both large and small firms each play a significant role in a networked environment (Langlois, 2003; Rothwell, 1994). In this model importance is placed on the coupling of the specialised knowledge of small firms to the greater product development and distribution capabilities of large firms through licensing agreements, joint ventures and other alliance structures. This imperfectly parallels the distinction between “component innovation” and “systems innovation”, with the large firms exploiting an integrative competence. In the view of Arora, Fosfuri and Gambardella (2001) this ‘division of labour’ has created a market in technology. One possible shortcoming of this perspective for the innovation process more generally is that it focuses on the hierarchical relationship between large and small companies, whereas much of the early development in many technologies takes place through the shared knowledge of smaller start ups. However, if the respective roles of large and small firms in “systems innovation” and “component innovation” is kept in mind no such shortcoming exists.

Where the approach adopted by 'open innovation' is somewhat unique is the primacy afforded to the role of the business model in determining whether or not a technology firm is likely to be successful (Chesbrough, 2003, 2006a, 2006b). Chesbrough and Rosenbloom (2002) suggest that the business model of a technology company is the construct that mediates the value creation process between the technical and economic domains, selecting and filtering technologies and packaging them into particular configurations to be offered to the market.

2.3 Implications for Policy Analysis for the Converging Technologies

It is apparent that the theoretical ideas reviewed above are more consistent and mutually supportive than their proponents may suggest. We draw four such mutually supportive ideas from this analysis, to provide a framework of policy analysis and prescription.

- *Investments in Intangible Capital*. New GPTs are likely to require massive investment in intangible capital, at both the aggregate and the organisational level. Such investments will need to cover all elements – human, organisational, managerial and production technology capital – and this list should be extended to include relevant forms of social capital (such as the ability and willingness of the community to understand and, where appropriate, accept the emergence of new GPTs).
- *Strategic and Complementary Assets at the Firm Level*. Effective innovation at the firm level will require the development and nurturing of strategic assets, such as core competences.
- *Networks and Alliances*. At all levels of the technology value chain, participation in global networks and alliances is likely to be central to achieving a competitive outcome. This applies from academic research, where research collaborations are increasingly widespread and powerful, down to the final step of successfully marketing a good or service to a final user.
- *Business Models*. It is not to be expected, for a number of reasons, that a single business model will fit all forms of technology commercialisation. Careful attention to the appropriate business model, given the wide variety of factors impacting on an individual company, is a prerequisite for success.

3. Key Characteristics of the Technologies and their Application Context

In this section we review, on an empirical basis, some of the key characteristics of the converging technologies and of the contexts in which they are being developed and applied. If the theoretical framework discussed above is indeed relevant we would expect considerable overlap between the main factors identified theoretically and those identified on empirical grounds below.

3.1 Diversity

Each of the GPT technologies is at various stages of development and importance – ICT is well established as the basis for a large sector within the economy, while the application of biotechnology has been delivering new products in a few well-defined industries and small-scale (nano) technologies are still in their infancy with a small range of products.

Each is a broad category made up of suite of component technologies, which can result in a multitude of different applications or products. These specific technology application areas often have important differences in characteristics. Successful commercialisation strategies require an understanding of the differences and similarities among the different types of products based on each specific technology or combinations of technologies.

Table 2 illustrates for a range of applications how these characteristics differ for a range of features of the commercialisation process. These features include the capital requirements, the length of the development period, the importance of IP protection, the nature of the underlying knowledge and characteristics of the product and its market. The outcome of the interaction of these features is that there is large diversity of commercialisation pathways for each of the applications. It is appropriate for some to be commercialised by large companies, others by small companies. This is a product of the interaction of the various features. Under past models of innovation, it may have been expected that applications with large capital requirements and large markets would be commercialised by large companies. It is one of the features of commercialisation of GPTs, however, that small companies can effectively participate in this process by employing alliances and participating in networks to overcome the shortcomings of size. This be will be discussed further in section 3.2.

Some of the features of the commercialisation processes for particular applications are discussed in the two sections below under the heading s of product development and production to illustrate the diversity of the application commercialisation pathways for various GPTs.

Development

The development period and the expense involved in developing an application based on a new technology or in developing the technology itself is a major factor in the commercialisation process. In the pharmaceutical industry, DiMasi et al. (2003) have estimated that it costs over US$800 million on average to undertake the R&D necessary to bring a new medicine to market, once the cost of failures and the opportunity cost of capital have been accounted for. The length of time between initial discovery of a potential drug candidate and its market launch is usually at least 8-10 years. The cost of development is mainly incurred in the clinical trials necessary to demonstrate safety and efficacy, particularly in Phase 3 trials which can involve thousands of patients.

This expense forms a significant barrier for new companies seeking to become fully integrated pharmaceutical companies. While established pharmaceutical companies can finance the development stage of new drugs through the sales of drugs already on the market, start-up biotechnology companies must rely on financial institutions, especially venture capital organisations and individual investors in the early stages.

The history of the biotechnology industry over the past 30 years shows that it is very difficult for biotechnology based companies to achieve the size of pharmaceutical companies and their fortunes are significantly affected by cycles of investor interest. Therefore beyond a certain point in the development process – usually in Phase 2 or 3, most biotechnology companies developing new drugs will rely on a funding alliance with an established larger company – usually a pharmaceutical company and sometimes a large biotechnology company (Rasmussen, 2006b) .

The capital requirements during the development stage are likely to be less onerous for veterinary pharmaceuticals based on biotechnology because the testing requirements are less stringent. However the difficulty with such products is that they will not obtain the prices that human pharmaceuticals can command.

Genetically-modified animal or plant organisms are also likely to have smaller capital requirements during development but face other barriers such as consumer resistance and the ability to fetch prices significantly higher than for non-modified products.

The amount of expenditure on R&D by biotechnology companies specialising in the development of platform technologies, such as diagnostic testing and micro arrays, is also likely to be less than for human drug development again because the lead times are less. However platform technologies are heterogeneous and the amount of development expenditure required will depend heavily on what kind of products or systems are being developed.

Bioinformatics products which combine certain types of platform technologies such as arrays with access to databases of lead candidates or genomic and proteomic sequencing data and accompanying software systems are an example of a platform technology used in research programs within both pharmaceutical and biotechnology companies (Rasmussen, 2006b).

The development costs vary considerably both within and between of different kinds of ICT. Semiconductor design is a task requiring sophisticated skills particularly as complexity increases with the number and types of circuits and in the design of hybrid structures incorporating communications and sensing capabilities. Nonetheless the short product cycle of most semiconductor products limits the expense that can be incurred. Similarly the development of ICT peripherals such as storage, printing, and other input and output devices is governed by product cycle times in months rather than years.

The cost of software development is largely governed by the type of application. The development of new operating system software can be very expensive and typically has a life cycle of around 5 years. New versions of other major software systems such as office productivity software, and systems governing large scale financial, logistical and manufacturing operations have a similar cost and time scale. On the other hand smaller scale software development costs are likely to be modest.

Applications based on small-scale technologies vary considerably in their complexity and the amount of time and cost involved in their development. The R&D requirements for unstructured nanomaterials or nanoparticles used for coatings or additives are likely to be quite modest while for structured materials such as fullerenes and carbon nanotubes which are more complex, the cost will be higher. Creating micro and nano-scale structures such as those used in microfluidics are more complex again while devices such as sensors that combine biological sensors with semiconductor substrates are the most complex.

For all these products based on small-scale technologies however the cost of development does not approach that involved in developing a new drug, except for those products that, such as dendrimers that used as novel drug delivery systems.

Production

The production of new technology products also varies across a number of features of the commercialisation process but one of the most important is capital requirements.

At one extreme is mass production of semiconductor products such as CPUs and memory chips. Mass markets for products that incorporate these products such as personal computers and associated peripherals and virtually all consumer electronics require the unit cost to be low. This means that manufacturing plants must be large and highly automated and therefore costly. Because the product cycle for semiconductor products is so short, the machinery in such plants must be regularly upgraded adding to the expense.

Large-scale production of semiconductors can only be undertaken by large companies such as those that dominate the ICT industry or by dedicated semiconductor manufacturers. This cost represents a formidable barrier for new companies seeking to enter the semiconductor manufacturing industry.

The capital costs of production are not as large for the manufacture of other ICT hardware such as hard drives and other input and output devices, or for the assembly of ICT components into systems such as personal computers or communications equipment. Labour cost become more important resulting in a shift in production to lower cost countries, initially Taiwan, Korea and Malaysia and now China. However, with no resource-based locational determinants, semiconductor manufacturing tends over time to follow the market and collocate with the manufactures and assemblers that are its customers.

Software production requires little in the way of upfront capital expenditure, the main cost being in the labour involved in both the development and production stages. Similarly ICT services are highly labour-intensive. Cost of labour is important, but skills, scale and business models are also vital in these industries. Substantial parts of software production and ICT services have relocated to countries such as India as they seek skill/wage tradeoffs using innovative business models (i.e. the globalisation of software and services is asset and efficiency seeking).

The production of traditional small molecule medicines is undertaken in plants with moderate capital costs and well understood technologies. Large-scale processes ensure that most medicines can be produced from relatively few plants around the world at relatively low unit costs. Because the barriers to entry for pharmaceutical manufacture are relatively low, patent protection becomes extremely important for the developers of new medicines. Patent protection ensures that the developer has a period of time as exclusive supplier to recoup the large costs of development.

Biotechnology-based medicines on the other hand usually have much higher unit costs. These medicines are often naturally occurring compounds in the body or their analogues and often occur at low concentrations. Producing these in sufficient quantities while ensuring high purity is expensive.

The production costs for platform technologies will depend on their exact nature. In the case of bioinformatics, for instance, the production of genomic and proteomic data was initially very expensive, but has fallen dramatically as new automated analytic techniques have been introduced. The cost of producing diagnostic arrays has also fallen sharply mirroring developments in semiconductor production. The software analysis that is usually part of bioinformatics systems follows the same cost of production as other software products.

Within the applications of small-scale technologies, the capital costs of production for nanomaterials and nanoparticles do not seem to be high so barriers to entry are low. Because of this there are opportunities both for specialist providers of these materials and for the incorporation of their production within larger companies.

The production of small-scale devices relies on some of the techniques used in semiconductor manufacturing, but usually can utilise earlier vintage plant meaning that production costs are not as high as for current generation semiconductors.

3.2 The Different Domains of Intellectual Property Protection and Open Access

Effective intellectual property protection is important when development costs are significant, there is only a fixed amount of time to recoup these costs in the market, product cycle times are not short and there are no significant barriers to entry by competitors. This is pre-eminently the case for traditional human pharmaceuticals, and to a lesser extent those based on biotechnology, where the protection provided by patents is crucial. IP protection is also important for companies seeking to produce genetically-modified plants and animals to be supplied on a regular basis to growers.

Companies producing platform technologies have found it more difficult to retain exclusive rights to the information relating to genomic and proteomic sequences which have quickly found their way into the public domain.

Because product cycles are shorter than in pharmaceuticals, ICT products have less reliance on IP protection. Nonetheless IP protection is still important in the design and manufacture of semiconductors and copyright is important for software. Overall however ICT has led the way towards open innovation (Chesborough, 2003, 2006) in which innovation is networked with active use of contract services, alliances and licensed technology. Importantly, a number of key areas of ICT innovation and development (e.g. the Linux operating system) use an open model (open source, open access, open innovation) in which individuals and firms of all size participate. This is, perhaps, the leading expression of networked open innovation, which feeds into innovative business models that extend the logic of the integrative competence of large firms that bring to market systems and services (e.g. installation, operations, support and maintenance services).

For nanoparticles and nanomaterials and for small-scale complex structures patents probably do not provide a great deal of protection. Obtaining desired characteristics in materials from controlling particle size is more a function of controlling the manufacturing process rather than the composition of the material, and building small-scale structures is likewise determined by control over manufacturing processes.

Intellectual property protection depends on being able to codify the knowledge embodied in the technology or its application. Codified knowledge is knowledge that can be specified exactly in the form of a patent description, lines of software code or in a manual. Tacit knowledge on the other hand is knowledge that is accumulated within a person or organisation and is not recorded in a codified fashion.

Companies can obtain and exploit a comparative advantage in the market by their ability to develop products and/or processes that incorporate both codified and tacit knowledge. This advantage can persist over time if the accumulated tacit knowledge can be retained and built upon, mainly by being able to retain and recruit skilled personnel.

IP: Results from Case Studies

The key role of intellectual property has been considered in several case studies of converging technologies involving nano biotechnology (Starpharma and dendrimers) and bioinformatics which have attempted to gain a better understanding of the role of patents in the commercialisation of these technologies. It has also received attention in work on open source in ICT systems and open access to research more generally. This work has suggested quite significant differences in IP regimes (and business models) adopted in the various technologies, with the level of complexity in the integration of component innovations and maturity in systems innovation and business models based on established integrative competencies determining the appropriateness of the various regimes.

The dendrimers/Starpharma case study suggests a need for strong patent protection as a necessary condition for successful start-ups (if the start-up is a component innovator using an IP-based business model). The bioinformatics case study is less clear-cut about the value of patent protection. The work on ICT suggests that there is trend to more open styles of innovation often based on open source and open access models. The pharmaceutical industry has relied heavily on patents to provide protection against copying over the long and expensive product development period. ICT on the other hand has not utilised patents to the same degree, but rather relied on short development cycles and speed to market for competitive advantage. It is not surprising therefore to find more open innovation models adopted in IT, while biotechnology retains the importance of patents. Nevertheless, developments in biotechnology and bioinformatics do often depend upon open access to data (e.g. the human genome) and are increasingly developing open-bio alternatives (e.g. Cambia).

Both dendrimers and bioinformatics are general purpose technologies developed at the convergence of nano/bio and bio/IT, respectively. The case studies suggest that dendrimers at least in so far as its pharmaceutical application is following the biotechnology model. The dendrimers/Starpharma is a case where IP for the general purpose technology (dendrimers) is tightly held and Starpharma has been able to obtain the exclusive licence to use the technology in pharmaceuticals, effectively blocking competitors from using dendrimer technology for pharmaceutical applications.

The fate of the bioinformatics ‘pioneers’ raises questions about the value of the patent protection, which they obtained. All of the ‘pioneers’, which sought to on-sell or licence their bioinformatics technology services to pharmaceutical and biotech companies, either failed or were transformed into drug discovery companies. In part this failure arose from the genomics libraries that formed the basis of their business becoming ‘open access’. For this reason, by becoming drug discovery companies they internalised the use of the bioinformatics technology and external IP protection in the form of patents became less important. Affymetrix, which combined its expertise in genomics with IT/bioinformatics to create a product, the ‘gene chip’ is perhaps alone in requiring continued patent protection for its bioinformatics technologies.

3.3 Networks and Alliances

Alliances in business have a long history, but over the past couple of decades they have become an important feature of business organisation to such an extent that Dunning, a prominent researcher of multinational enterprises since the 1950’s, has described this new trend as ‘alliance’ capitalism. In his view this has been brought about by and a series of landmark technological advances, as well as globalisation (Dunning, 1995).

Dunning outlines five reasons for the growth of alliances arising from the impact of technological advances. These are to:

- enhance the significance of core (general purpose) technologies;
- increase the interdependence (convergence) between distinctive technologies for joint supply of a particular product;
- truncate the product life cycle; and
- upgrade core competencies as a means of improving global competitive advantages.

Each of these reasons has been confirmed by the work on GPTs undertaken in this project. The development of biotechnology and ICT and its convergence as ‘bioinformatics’ has been shown to be strongly associated with the formation of alliances between large and small firms and between small firms, and between firms of all sizes and other players in the innovations system (e.g. universities). Established technology companies have scrambled to upgrade their core competencies and selectively acquire the new knowledge being generated with the development of the new GPTs.

This rapid expansion in alliance formation represents a significant change in the seemingly inexorable trend toward larger and larger vertically integrated firms as documented by Chandler (1977, 1990). Since that time, however, increasing standardisation and specialisation has led to more extended and more complex production chains/systems, in which players of all sizes can play a part. Alliances are an intermediate form of business organisation that is not inconsistent with the development of the vertically integrated multi divisional firm, but which also facilitates the formation of small scale start up firms associated with the commercialisation of new technologies. While alliances are strongly associated with the transfer of technology, they are also formed for a range of reasons, including manufacturing, marketing and distribution.

In this new industry structure, technological development is often led by a cluster of small new firms, rather than emerging from the laboratories of large firms, as was typical of an earlier era. This has led to highly disaggregated value chains that have encouraged firms to form networks of alliances with other firms contributing to the value chain. Not only have these alliances been formed to transfer complementary technologies from small to large companies, but they have also been formed between small specialist firms, to enable them to combine their expertise, to fully develop products and services that contributed to the value chain.

The converging and complementary nature of GPTs is such that firms that develop a particular specialisation in one technology require other complementary technologies to complete, or further develop, their specialised technology, products and processes (Teece, 1986; Hagedoorn et al., 2000). The tacit quality of the knowledge base, or the nature of the required technology, is such that it can neither be acquired on the open market nor developed in house. However the technology can be developed and modified to meet particular requirements in an alliance structure. This transfer is achieved more readily where the knowledge is more easily codified.

Arora, Fosfuri and Gamberdella (2001) identify a series of changes in the markets for technology that have improved the ease with which technology can be transferred. In general transferability is improved if the technology can be decomposed into independent tasks and commoditised, that is, if the technology can be embodied in a product that requires little tacit knowledge to use it. In some industries with long product development time frames, patents are of particular importance in this process. This clearly establishes ownership of the intellectual property developed, or made available to the alliance, and will protect the innovation from expropriation by potential partners (Gans and Stern, 2003).

The ease with which software can be codified, transferred globally via the web and reintegrated with other software has increased the degree to which industry participants in ICT can be easily networked. It has also undermined the ability of firms to defend their intellectual property and drastically truncated product life. Increasingly this has led to the adoption of an ‘open source’ model of industrial organisation for ICT firms. Profitability depends on swiftness to market with products compatible with ‘open source’ platforms.

In biotechnology a different set of dynamics apply. The ability to effectively protect innovation in drug discovery, through patents, has enabled small biotechs to partner large pharma, without fear of expropriation and encouraged partnerships that combine the technological precocity of the biotechs, with the product development and distribution might of the large pharmaceutical companies.

However at the convergence of biotechnology and IT, this project has demonstrated that life for innovative bioinformatics firms is much less comfortable. While they have been just as active in alliance formation, their dynamics have much been closer to that of IT firms, with patents affording little protection, for innovative services in bio-related software and data management, against low price competition from developing countries.

3.4 The Diversity and Fragility of Business Models

Many industry sectors adopting GPTs are characterised by considerable instability. Many start-ups have a short life. Mergers and acquisitions, both large and small are frequent. Alliances are formed, as companies seek product and other support to fund their R&D programs, and terminated, when product development fails. Moreover the strategic direction of companies is sometimes radically transformed and they seek to reinvent themselves when research programs fail. One of the case studies, Proteome Systems, is an example of a failing platform technology company, which transformed itself into a drug discovery company, during the course of the project.

In seeking to better understand this industry turmoil, it is suggested that the structure of the business model being employed by these companies should give insight into the reasons for success, transformation or failure of various types of firms comprising the industry.

The concept of the business model grew out of a need to encapsulate the essential features of a business in a short descriptive document in order that a judgement could be made, for example by potential investors, on whether the business was likely to achieve its financial and other objectives. In this context the business model is designed to answer a series of questions essential to any business – who are the customers, what do they value, how that value can be delivered to the customer at an appropriate cost and how the business deploys its assets. It includes a description of the key assets, both physical and intangible such as intellectual property, governance structure and management. It consists of both a *narrative* of how the business works and the *numbers* – how it makes a profit.

Chesbrough and Rosenbloom (2002) suggest that the business model of a technology company is the construct that mediates the value creation process between the technical and economic domains, selecting and filtering technologies and packaging them into particular configurations to be offered to the market. They argue that this requires consideration of many facets of the firm's operations. They suggest that the functions of a business model are to:

- articulate the *value proposition*, that is, the value created for users by the offering based on the technology;
- identify a *market segment*, that is, the users to whom the technology is useful and for what purpose;
- define the structure of the *value chain* within the firm required to create and distribute the offering;
- estimate the *cost structure* and *profit potential* of producing the offering, given the value proposition and value chain structure chosen;

- describe the position of the firm within the *value network* linking suppliers and customers, including identification of potential complementors and competitors;
- formulate the *competitive strategy* by which the innovating firm will gain and hold advantage over rivals. (2002, p. 7)

With respect to business models, this study confirms Chesbrough's view that the construct of the business model, with its structured framework for considering the way economic value is generated, is one of the most important concepts in predicting the ultimate success or failure of the commercialisation of the technology. At the heart of the business model for a technology company, is how the firm expects to raise its revenue at a sufficient level to fund its ongoing R&D program. For start-up firms there are two clear models. One seeks to raise revenue by licensing its technology on a fee for service basis. The other is to use its particular technological expertise in developing a product capable of generating the required revenues. Both models may seek support from larger partners to fund the R&D in return for royalties or other revenue share arrangements.

It is apparent from the study made of the commercialisation of bioinformatics by the initial IP leaders, that the bioinformatics businesses of the companies that adopted a fee for service business model generally failed. The single clear success of the group of companies, Affymetrix, adopted a product revenue model. It is still too early to judge whether those companies that have internalised their bioinformatics knowledge to use in their own drug discovery programs have been successful. Although some of the IP leaders of the group, such as Curagen, have advanced drug development pipelines, their future depends on the probabilities of success common to other drug discovery companies.

In areas of greater maturity, such as ICT, both product chains and systems are more extended and complex, lending an additional dynamic to the process. Crucially, many start-ups have only a small piece of the puzzle (i.e. one component in a much larger system), such that they cannot complete a business model without external support – be it through alliances or dependence upon open components (e.g. open source software objects and libraries). The "dot com" boom featured many examples of incomplete business models. As individual business many failed, but the internet did not go away and there have been many major successes, including new niche innovators turned integrators (e.g. Google), new component innovators (e.g. Skype, now taken over by e-Bay as the component is integrated into broader communication and marketing systems), and new systems innovators and "e-integrations" (e.g. IAC/InterActiveCorp.).

4. Implications for Australian Policy

The discussion to date has introduced general purpose and converging technologies, distilled key themes from the literature on general purpose technologies and innovation and illustrated the relevance of that framework in terms of a discussion of various features of the converging technologies and the conditions of their development and application. Here, starting from the premise that the economic and social impact of the converging technologies will be so profound that a coordinated and substantial national response is necessary, we draw from that analysis five principles for consistent national policies for the converging technologies, and make some preliminary suggestions as to how they might be applied.

4.1 Strengthening the Foundations – Tangible and Intangible Assets for Converging Technologies

The foundations for competitiveness lie in those factors that underpin investment in tangible and intangible capital for these technologies. This covers a wide range: physical or tangible capital, including infrastructure, human capital, R&D and related technological capital, other forms of intangible capital of organisations, including but going beyond firms, and relevant forms of social capital. The latter covers, for example, the willingness of the public to support the adoption of new technologies. Increased investment in some of these areas by governments, and measures to induce such investment by others on a large scale, will be necessary to meet the challenge of the converging technologies. Three examples of areas in which such investment is required – infrastructure, technical skills and public understanding - are noted briefly below.

There is no simple specification of what is required to create such a world class infrastructure for the converging technologies in Australia. There is a complex, synergistic relationship between infrastructure, research and commercial development. A basic level of infrastructure is required to make both research and commercial development possible, and advanced infrastructure in a suitable environment will greatly stimulate both R&D and the application of new technologies. But the progress of R&D and commercial application will change and increase infrastructure requirements, while also increasing funding options. For these reasons the specifics of infrastructure requirements need to be a matter for continuing assessment, in the context of emerging research and commercial activities and in conjunction with those expert in these trends and their international context.

Small scale technologies, in common with other emerging technologies, will require new and upgraded skills at the technician level as small scale technologies become increasingly common in industry. For instance, the development of specialised nanomaterials, such as nanocomposites and nanopowders, may have an impact similar in scope to the introduction of plastics and composites in earlier decades. This may require a substantial overhaul of certificate level courses in areas such as process manufacturing, engineering, chemical processing and powder coating. This requirement for overhaul is likely to apply to other areas of education and training, and to other elements of the set of converging technologies.

Finally, systematic implementation of major new technologies can, and should, be implemented only on the basis of informed consent from the community. Given the potential revolutionary impact of some of these technologies, there is a need for further investment in structures to strengthen the capability of the Australian community to reflect on these issues, and the social and ethical questions that they raise, in a considered and informed manner.

4.2 Increasing Global Integration – Building Networks and Alliances

Deeper integration into global networks and alliances is necessary for competitiveness at all levels of the value chain, from basic research to product marketing. Sustained attention needs to given to ways of supporting this integration, especially in relation to newly emerging research and application centres such as in China and India. However experience of successful programs is limited, especially in relation to the involvement of firms, and some experimentation might be required.

One example of such a program is that established in 2006 by the Australian Government, in conjunction with the Government of India, with an allocation of $20 million over three years for the Indo-Australian Fund for Scientific and Technological Cooperation. Jointly managed by the Australian Government Department of Education, Science and Training and the Indian Government Department of Science and Technology, the Fund will support collaborative activities through projects that build productive alliances, enhance opportunities for Australian and Indian expertise, and create opportunities for researchers, in both the private and public sectors in both countries. It does seem to be focused only at the research stage, however, and is on a fairly small scale, even for one country.

A generalisation of such a program - across technologies, countries and participants in the supply chain – would be worth detailed examination. Such a program might, for selected countries and technologies, support private firms embarking on knowledge based collaborations with foreign counterparts, and encourage universities and government agencies to enter into such relationships. This could provide funding, on a competitive basis, to joint R&D activities, to local companies developing products in conjunction with overseas partners, to government agencies embarking on research or development activities with their foreign counterparts, to shared R&D and teaching activities and so on.

4.3 Developing Australia as a Global Centre for Converging Technology Applications

Australia can at best be a niche player in basic research and product development in these areas, and such efforts should be supported. But it can become a global centre for some applications of the converging technologies, and this is beginning to occur already in some areas. Those applications areas that involve low capital cost and can draw heavily on open access technologies, yet address large markets with customised products, would seem particularly appropriate for Australian skills and circumstances. In our area this goal should be systematically pursued by integrated policy initiatives.

In an earlier report for the Victorian Government (CSES 2003) we suggested two initiatives to develop leading edge applications of converging technologies on a globally significant scale. In the present context, one would be directed at developing a greater awareness of the potential benefits of applications of the converging technologies within Australian and to encouraging creative thinking within industry about how the technology can be utilised. The proposal is to establish an extensive program of demonstration projects. Such a program would aim to show, through practical and concrete examples, the benefits that can be achieved through the application of small scale technologies.

A Demonstration Projects Program might could have the following characteristics: Projects would be invited from individual companies or consortia of companies. Projects must have as an outcome the development of an application of benefit to the company or companies, such as a new product or process. There should be similar applications potentially available in other companies and industries The project must utilise small-scale technology as a crucial part of the project, although other technologies can also be used. Project participants must agree to participate in a program publicising the results of the study, subject to reasonable confidentiality requirements.

The other proposal is to establish of a range of Applications Development Consortia. Consortia of various types are widely used in the US and in other countries to facilitate the development of commercial applications of new technologies. Such a consortium might consist of at least working together to develop and apply small scale technologies in their businesses, in a particular technology or business area. They would come together, with Government support, to undertake jointly a range of activities R&D, business development and other activities.

4.4 Providing Increased Support across a Range of Different Commercialisation Paths and Business Models

Australian firms face many barriers to achieving a viable position in global markets, arising from isolation from the main intellectual and business centres and the scale and immaturity of domestic markets. Increased public support to assist them to enter global markets is required, in ways that respect the diversity and fragility of business models. The objectives and nature of such support programs require further consideration in the light of the issues reviewed in this report, but it would be crucial to maintain balance between the many different commercialisation paths, business models and intellectual property protection or open access regimes that firms utilise.

4.5 Coordinating Policies Across Technologies, Applications and Agencies – Focus Limited Resources in the Face of Intense Competition

Finally, given the convergence of technologies and our small scale in the face of intense global competition, it is necessary that national policies be coordinated in several dimensions: across technologies, across application areas and across the national and the state governments.

5. Conclusion

This paper is a preliminary contribution to the development of an appropriate policy framework for Australia to meet the fundamental challenge of the converging technologies and the general purpose technologies to which they are giving rise. Its intended methodology, incompletely applied at this stage, is to derive the guiding principles for such a policy framework from both a theoretical and empirical analysis of the technologies and the conditions of their application, and of the Australian context, and to examine in detail specific policy proposals to give effect to those principles.

Further work will attempt to base the policy principles on a more rigorous and complete analysis, both theoretical and empirical, than has been possible here, and then to review possible policy options consistent with them in detail.

Table 2. Characteristics of Development and Application Pathways for Converging Technologies

Development and application areas	Development phase	Capital requirements for R&D	Capital requirements for production	Importance of IP protection	Codified or tacit knowledge	Product cycle time	Commodity or customised product	Size of market	Commercialisation pathway
ICT									
Semiconductor manufacture	Short	Medium	Large	High	Codified	Short	Commodity	Large	Large company
Semiconductor design	Short	Small	Small	High	Codified	Short	Customised	Small	Specialist company
ICT equipment assembly	Short	Medium	Medium	Low	Codified	Short	Commodity	Large	Large company
Software production	Medium	Varies	Small	Medium	Tacit	Short	Customised	Varies	Varies
Integration	Short/medium	Small	Small	Limited	Tacit	Short	Customised	Large	Varies
Industrial and commercial applications	Short/medium	Small	Small	Limited	Codified and tacit	Short	Customised	Very Large	Many types of organisation
Biotechnology/Biomedical									
Drug development and manufacture	Long	Large	Medium	Very	Codified	Long	Commodity	Medium/Large	Large company
Drug discovery	Long	Medium	Small	Very	Codified	Long	Customised	Large company	Many types of organisation
Platform technologies	Medium	Medium	Medium	Medium	Codified	Medium	Customised	Small/medium	Specialist company
Plant/food applications	Medium	Medium	Medium	Very	Codified	Medium	Customised	Medium/large	Large/specialist company
Veterinary applications	Medium	Medium	Medium	Very	Codified	Medium	Customised	Medium/large	Large/specialist company
Bioinformatics	Medium	Medium	Small	Very	Codified	Medium	Customised	Small/medium	Specialist company
Industrial and commercial applications	Short/medium	Small	Small	Little	Codified and tacit	Short	Customised	Very Large	All types of company
Small-scale technologies									
MEMS/sensors	Medium	Medium	Medium	Medium	Codified	Medium	Customised	Small/medium	Specialist company
Microfluidics	Medium	Medium	Medium	Medium	Codified	Medium	Customised	Small/medium	Specialist company
Nanomaterials/nanoparticles	Medium	Small	Small	Medium	Codified	Short	Customised	Medium/large	Large company
Nanodevices/sensors	Medium	Medium	Medium	Medium	Codified	Medium	Customised	Small/medium	Specialist company
Industrial and commercial applications	Short/medium	Small	Small	Little	Codified and tacit	Short	Customised	Very Large	All types of company

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