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Challenges and Opportunities for Innovation through Technology: The Convergence of Technologies

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FOREWORD

Specific interest in "converging technologies" and "technology convergence" has been growing in scientific, technological and policy circles since the beginning of the 2000s. Potential benefits stemming from the convergence of Nanotechnology, Biotechnology, Information Technology and Cognitive Sciences (NBIC) were widely discussed at that time, especially in terms of expected improvements in human performance and health, and this enthusiasm often manifested itself in terms of funding, particularly for nanotechnology.

However, in both the literature and discussions on "converging technologies" and "technology convergence", a distinction is emerging between the two terms. "Converging technologies" is most frequently used as an umbrella-term referring to groups of technologies with potential links between them and resultant synergies and benefits. As such, the term is routinely used in policy circles when considering future options, discussing priorities, formulating policies and implementing new support programmes. "Technology convergence", on the other hand, tends to refer to specific examples of actual convergence between particular technologies and the ways in which this convergence manifests itself in terms of the impacts on research activities and the development of scientific and technological communities. As such, it is more closely related to actual research and innovation activities in public laboratories and in firms than it is to broader policy discussions. While the term "converging technologies" continues to have connotations of future promise, the term "technology convergence" affirms the current realisation of this promise.

This report focuses attention on specific instances of technology convergence and the opportunities and challenges they create. It confirms that convergence is not limited to futuristic visions of technologies for enhancing human performance (the original promise of the early 2000s), but can be observed today in actual instances of the convergence of scientific communities, of the emergence of new technology production and manufacturing infrastructures, and of the complex embedding of technologies into society. Moreover, by examining instances of technology convergence in multiple areas, such as synthetic biology and bio-photonics, this report identifies a number of potential issues that may require further consideration.

This document is the final report of work on challenges and opportunities for innovation through technology performed as part of the 2011-2012 Programme of Work and Budget (PWB) for Output Area 1.3.2 (Science and Innovation Policies). It was developed by the Secretariat of the Committee for Scientific and Technological Policy (CSTP) with separate inputs from Christien Enzing (Technopolis B.V.) and Douglas K. R. Robinson (Teqnode B.V.). It was submitted to the CSTP for review and approved on 31 October 2013.

Note: The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

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EXECUTIVE SUMMARY

Interest and excitement in converging technologies developed in the early 2000s. Particularly visible at this time was the NBIC[1] programme, which envisioned that the combination of different disciplines into new research and development (R&D) fields would lead to synergies in the form of technological innovations that would not only shape human lives but also enhance the human body to improve performance.

More than a decade later, the enthusiasm and excitement about new mixes of key enabling technologies remains, though the main driver is now the potential to address grand societal challenges. This report describes the evolution of the original converging technology vision to the present day, and notes this may in fact be one manifestation of a broader dynamic – that of technology convergence.

In both the literature and discussions on "converging technologies" and "technology convergence", a distinction is emerging between the two terms. "Converging technologies" is most frequently used as an umbrella-term referring to groups of technologies with potential links between them and resultant synergies and benefits. As such, the term is routinely used in policy circles when considering future options, discussing priorities, formulating policies and implementing new support programmes. "Technology convergence", on the other hand, tends to refer to specific examples of actual convergence between particular technologies and the ways in which this convergence manifests itself in terms of the impacts on research activities and the development of scientific and technological communities. As such, it is more closely related to actual research and innovation activities in public laboratories and in firms than it is to broader policy discussions. While the term "converging technologies" continues to have connotations of future promise, the term "technology convergence" affirms the current realisation of this promise.

By examining instances of convergence of technologies in multiple areas, such as synthetic biology and bio-photonics, this report identifies a number of potential issues that may require further consideration, including the following:

- An overemphasis on the converging technology umbrella-label, although useful for priority setting (for funding programmes and policies), may inhibit technology convergence in research and in product development;
- Instances of technology convergence show different characteristics in terms of multi-, inter- and trans-disciplinarity. Each form requires different co-ordination strategies and policies;
- Co-ordination and integration at the level of scientific research is a major issue for convergence, particularly in terms of the development of scientific instruments, types of research cultures and availability of skilled technicians;
- Commercialisation of converging technologies poses a great challenge in terms of intellectual property management strategies and the development of new business models;
- The technology production infrastructure that needs to be in place to transform techno-scientific knowledge into products and applications in society has to be part of the discussion of technology convergence, particularly where incumbent value chains come together;

- Societal uptake and adoption of converging technologies requires particular policy attention due to the complexity of many of the emerging technologies, their multiple potential uses and the variety of governance challenges posed; and
- Consideration of public opinion in the design and deployment of converging technologies is a considerable challenge. With the increasing emphasis on public involvement in R&D and the growing theme of responsible research and innovation, a further understanding of the forms of this involvement, the range of experiences and best practices, will be required. Public engagement and social science studies of converging technologies would be more fruitful if the dominance of speculative discussions of human enhancement were complemented by using illustrative instances of convergence in particular domain contexts (health, energy, transport, etc.).

I. INTRODUCTION

Specific interest in converging technologies has been growing in policy circles since the beginning of the 2000s, particularly in the United States and in Europe. Promises of the convergence of Nanotechnology, Biotechnology, Information Technology and Cognitive Sciences (NBIC) were apparent at that time, tightly coupled to an enthusiasm for those technologies (supported by funding, particularly for nanotechnology) and strongly linked to ideas of improving human performance and health. Although the initial promises have evolved into a variety of new forms, the topic of converging technologies is evidenced strongly in discussions of science, technology and innovation policy.

"Converging technology", as an umbrella term, has been promising potentially transformative changes to industries and societies throughout that time, initially with the projections of contributions to human enhancement[2] and more recently as potentially providing solutions to societal grand challenges, including managing mega-cities, global stewardship, clean water production and food security, to name but a few (Roco and Bainbridge 2002, Nordmann 2004).

In the past five years, there has been increasing excitement and interest in specific areas of convergence now moving high on the technology policy agenda, providing a stimulus to create roadmaps[3] and to develop dedicated research centres,[4] for example, in neuroinformatics (at the level of basic research)[5] and in synthetic biology. Converging technologies have also been evident in funding programmes, for example within the European Union Seventh Framework Programme[6] and in Japan, in the AIST Innovation Platform IBEC.[7]

This report focuses attention on specific instances of convergence, and the opportunities and challenges they create, enabling the identification of policy-relevant implications that may require particular attention. This report confirms that **convergence** is not limited to a futuristic vision of technologies for enhancing human performance (the original promise of the early 2000s), but can be observed today in actual instances of the convergence of scientific communities, of the emergence of new technology production and manufacturing infrastructures, and of the complex embedding of technologies into society. It is on the basis that there are visible examples of convergence that this report places particular emphasis.

The report presents the characteristics and implications of convergence in this and two subsequent sections, followed by a summary of potential policy implications and some concluding remarks.

The next section (Section II) provides the historical background that has led to today's interest in convergence. This is done through the description of the origins of umbrella terms such as "converging technology" and "NBIC" and traces the change in emphasis from discussions of labels of converging technology to a focus on instances of convergence between disciplines and sectors.

Section III explores the characteristics of technology convergence as seen today. It tackles this wide ranging topic through five entry points: 1) convergence in research (knowledge production); 2) commercialisation of the output of convergence research (knowledge use); 3) convergence in manufacturing and product development; 4) convergence in societal adoption; and finally 5) societal debate on convergence.

Section IV examines the implications of convergence and Section V offers concluding remarks.

II. THE HISTORY OF THE "CONVERGING TECHNOLOGY" UMBRELLA-TERM

This section considers "converging technologies" from different viewpoints. It begins with the original broad umbrella term that first sparked interest and support in the early 2000s. It then moves to describe the transformation of that interest into specific instances of convergence where concrete activities in research and innovation are taking place. The objective is to provide a funnel that guides the reader from the broad discussions of converging technologies to more specific descriptions of convergence.

Discussions about convergence of technologies have occurred several times during the past century, for example, in the rise of materials science since the 1950s, and in the notion of technology fusion, e.g. mechatronics (Kodama 1992). Information and Communication Technologies (ICT), since the 1970s, and biotechnology, in the 1980s, have also been argued to represent converging technologies/technoscience (Antón et al. 2001). In the 1990s, discussions revolved around the convergence of telecommunications, broadcasting infrastructures and services (particularly the role of the internet) (OECD 1997).

However, in the United States there has been high visibility of the particular umbrella-term "Converging Technology" since the early 2000s, linked to a research and technology policy initiative and to the acronym of "NBIC" (nano, bio, info and cogno).[8] Historically, the term NBIC, as used in the United States and adopted elsewhere, emerged at the time of the rise of nanotechnology, perceived initially as a platform for seeing how nanotechnology would impact other disciplines and industries (Roco and Bainbridge 2002). The US NBIC policy initiative stimulated great debate, especially with its focus on human enhancement (see Box 1).

Box 1. NBIC

There are no agreed definitions of "Converging Technology" and in the 2000s the term was used interchangeably with the acronym NBIC, which stands for combinations of nanotechnology (N), biotechnology (B), information and communication technologies (I) and cognitive technologies (C). The NBIC initiative in the United States has been argued to have not been a major policy initiative at all but rather a means, in the early 2000s, to argue for financial support for nanotechnologies by providing "visions" (rather than genuine roadmaps) for the development of converging technologies or a "new renaissance of science". (CONTECS Final Report 2009).[9]

An important point to make is that NBIC was originally a visioning exercise rather than an observation of a particular trend in science and technology research and development (R&D). However, it triggered much debate and interest and was closely tied to forward-looking activities related to nanotechnology, particularly around the vision of human enhancement applications. These debates remain today in discussions of ethical and societal aspects of NBIC, which often cite that vision of human enhancement (Beland et al. 2011, Ferarri et al. 2012).

Interestingly, the research support arm of the European Union (then DG Research) responded to the excitement that was generated, as well as taking a further step in developing specific descriptions of convergence by initiating an activity that led to the 2004 CTEKS report (Nordmann 2004). That report extended 'converging' to all sciences and technologies, and the development of a governance approach.[10] In a subsequent report commissioned by the European Parliament and undertaken by the European Technology Assessment Group (ETAG 2006), a similar approach to convergence was adopted. It emphasised that convergence was already occurring in laboratories and this required investigation, in addition to the strong future-visions in circulation at the time (cf. NBIC and human enhancement, see Box 1 above).

Looking elsewhere in the world, such as Asia, South America and the Middle East, there has been little use of the label of "Converging Technology" or "NBIC". In 2007, a programme promoting converging sciences and technologies was initiated by the National Science Foundation of the Israeli Academy in co-operation with the Israeli National Committee for Converging Technologies. The budget was USD 120-130 million for the period 2007-2012. In this programme, convergence was taken as a mode of inter-disciplinarity, and convergence could include more than the nano, bio, info and cogno elements of NBIC.[11]

Around the same time, other actors stepped into the discussions and debate about converging technologies, like the International Risk Governance Council (IRGC), which included converging technologies in its *White Paper on Nanotechnology Risk Governance.*[12]

Outside of governance and policy discussions, the European Group on Ethics[13] and social science researchers explored the societal and ethical consequences of converging technologies in the manner of NBIC. Particularly visible in the ethical and societal discussions were debates on human enhancement and the boundaries between health technologies and cosmetics (Swierstra et al. 2009).

About ten years after the two widely referenced reports (Roco and Bainbridge 2002, Nordmann 2004), neither the acronym "NBIC" nor the term "converging technology" holds the monopoly in terms of interpretations of convergence, which continues to be regarded as promising and is shaping many technology policy discussions. Today, NBIC continues in the activities of NBIC2,[14] which has broadened from the potential of the original disciplines of nano, bio, info and cogno for application to human enhancement towards more disciplines and additional scales.[15] NBIC2 couples convergence not only to human enhancement but also to broader societal challenges.

Elsewhere technology convergence is appearing as a dynamic in new promising areas of technological development. For example, a recent STOA-funded project *Making Perfect Life* (Van Est and Stemerding 2012) explored converging technologies by looking at two bio-engineering megatrends relating to convergence, representing an engineering approach to life.

The question of "*what is technology convergence?"* is being asked elsewhere in the world. For example, in the United States, the Massachusetts Institute of Technology (MIT) recently produced a white paper on the convergence of the life sciences, physical sciences and engineering (MIT 2011). The document actively moves away from the NBIC umbrella-term, and explores current and potential convergence of the life sciences, physical sciences and engineering in terms of inter-disciplinarity and added value from convergence. In its closing remarks, it points out that, alongside providing new combinations and transformative technologies, convergence will speed up scientific discovery.[16]

In Japan, the AIST further articulates technology convergence in its Photonics-Electronics Convergence System Technology programme (PECST). Here, a number of disciplines (electrical engineering, photonics and material/fabrication sciences) have been organised to augment the convergence of electronics and photonics for advanced chip design. This example is further detailed in Box 4 of section III.

In India, there is a heavy focus on specific areas of convergence within ICT as illustrated, for example, in a recent report by KPMG India (KPMG 2013). In research and higher education, the Centre for Converging Technologies at the University of Rajasthan[17] has produced a Doctoral and Masters programme that expands on the NBIC acronym, and explores particular instances of convergence between them. Elaborations of the acronym include expansion of the "B", which now represents bioinformatics and biotechnology, and the "C", which incorporates cognitive science and neuroscience.

This brief history of the discussions and activities on "NBIC" and "Converging Technology" shows a trend towards looking at specific combinations of disciplines and technologies as convergence. Amidst the variety of interpretations of what convergence is, or could be, a description of convergence is needed that is not limited to NBIC but includes other notions of convergence whilst capturing the essential elements that makes NBIC promising.

A common notion, seen in all of the definitions, is that convergence is more than the combination of different disciplines or technologies. It leads to synergies, adding more value through convergence. With this common characteristic, a broad description is proposed as a guide in this report:

"Convergence occurs where scientific disciplines or key enabling technologies combine with other disciplines or enabling technologies and promise new or added value beyond synergies".

This broad description can be further elaborated into three sub-categories, each related to a distinct area of application:

1. Convergence at the level of scientific research: where previously separate disciplines of science and technology become interlinked in the co-production of a new field of scientific research;
2. Convergence at the level of manufacturing and product development; and
3. Convergence in the embedding of technologies into socio-technical systems such as healthcare, logistics and food security.

In point 3, other technologies not envisaged with the original technologies become important and have to be integrated. With the current attempts to anticipate, at an early stage, embedding of new technologies into society (cf. ELSA (ethical, legal and social aspects), responsible research and innovation), this will actually modify the dynamics of development of converging technology.

III. CHARACTERISTICS OF TECHNOLOGY CONVERGENCE

This section explores five areas of convergence activity as it relates to: *a)* scientific research; *b)* commercialisation; *c)* product development and manufacturing; *d)* markets and the adoption of technology by society; and *e)* social studies and debate.

Scientific research

Convergence is seen in scientific research when previously disparate scientific communities come together to produce knowledge relevant to those various communities and stimulates an identifiable new community. Such coming together is not easy and poses tremendous challenges for those involved. For instance, when molecular biologists work with material scientists, there are different laboratory practices, different tools and instruments and different technical standards and protocols. New protocols and new scientific instruments have to be developed: in short, new research practices. This subsection will describe three dynamics – *i)* inter-disciplinary research; *ii)* convergence around technology platforms; and *iii)* agglomeration of actors in convergence hubs involved in convergence within scientific research.

i) Inter-disciplinary research

New fields of science and technology research emerge within or between disciplines. When they are *intra*-disciplinary, new fields emerge within a set of incumbent and stabilised practices and processes of scientific activity that regulate what is classed as "worthwhile" research. Within this stable framework, instruments are adapted, new research questions are created and new knowledge is added to the pool of scientific knowledge. Two examples would be high-energy laser physics and next generation lithography for semiconductor manufacture, both of which work on the same scientific principles and use the same tools and instruments (albeit with some further developments within each local field). New knowledge is produced and easily evaluated by a stable peer-review community.

When new fields are *inter*-disciplinary, they emerge as a mixture of approaches to doing research, using a variety of analytical instruments and without aligned ways of evaluating what is worthwhile. Fields of convergence in scientific research lie in such interdisciplinary settings, where new protocols, new analytical-instruments and new ways of evaluating worthwhile directions to explore are the norm.

Inter-disciplinarity has been at the core of the converging technology debate since the early 2000s (Nordmann 2004) and continues in the discussions today (OECD 2011). Convergence is the new combination of disciplines to create new fields of research, with dedicated communities. Such dedicated communities are visible when there are events (and other locations in which) to share knowledge (for example, via conferences or peer-reviewed journals). Other locations include agenda-setting forums (for the creation of shared visions, roadmaps, etc.).

One example of an area of convergence is biophotonics, the study of the interaction of light with biological/living material. In biophotonics, physicists, engineers and biologists come together to explore the interaction of light with a variety of living tissues at decreasing length scales (muscle tissue, individual cells, the surface of cells and within cells).[18] Such research promises applications in understanding the mechanisms of healthy and diseased tissues and organs, to inform therapy technologies. The challenge in bio-photonics is that physicists and engineers used to dealing with inert materials now have to incorporate living (and thus moving/dynamic) materials. This requires new techniques, instruments, etc.

Another example is synthetic biology (Benner and Sismour 2005, Andrianantoandro et al. 2006, Purnick and Weiss 2009) which has often been referred to in recent discussions of technology convergence. In synthetic biology, a variety of disciplines come together in a mixture of ways to create new synergies. The overarching idea is to apply an engineering approach to biological systems, looking at such systems as living mechanical machines and building devices from standardised biological building blocks (Boyle and Silver 2009). Thus, synthetic biology can be described as applying engineering principles to describe and construct biological systems and processes.

Box 2. A brief description of synthetic biology

Synthetic biology applies rational design from mathematics, engineering and computer science to the “wet-world” of living matter. Building functional constructs, which have reliable and predictable behaviour that do not exist already in nature, is the overarching vision at the level of research.

The field itself is not a coherent whole but is built on different combinations of disciplines such as biology, engineering, physics, chemistry, computer science and bioinformatics. For the purpose of this report, such constructs can be described as being used to perform tasks. R&D in synthetic biology (and associated promised future applications) can be partitioned into four broad goals that drive the research in this area (which are widely referred to in different ways in the many definitions of synthetic biology that are in circulation):

1. (MIMICKING) SYNTHETIC GENOMES: a top-down approach following models of genomes existing in nature, “synthetic genomes” are designed, produced and placed into bacteria to reproduce themselves. The approach has been pioneered by Venter and his colleagues (a closely-related field is genetic modification) (Gibson et al. 2010).

2. BUILDING FROM EXISTING PARTS: a biological bottom-up approach that does not take an existing living system/organism as the starting point, but uses biological parts to create new living circuits, devices and cellular systems *de novo* (Benner and Sismour 2005).

3. PROTOCELL: a chemical bottom-up approach which starts with the basic chemical compounds to create new/alternative forms of life (a closely-related field would be the various activities to create non-carbon based life) (Solé et al. 2007).

4. NEW GENETIC SYSTEMS: based on chemical modification of nucleic acid bases (a closely related field would be novel molecular systems, modelling and computation) (Chiarabelli et al 2009).

The order of the four groups within synthetic biology gives an indication of the degree of manipulation, synthesis and control of biological/living matter and systems (which increases as you descend the list).

It is important to note that there is no clearly defined synthetic biology community at present, but a mixture of communities, often with shared aims. There is a wide variety of tools, approaches and ideas regarding the most promising research directions. Though the community is not as yet stable, locations can be identified where research is published and events where results are shared.[19] In a recent analysis of publications in the Web of Science, (Oldham et al. 2012)) reveal the diversity of the publications on synthetic biology. In terms of journal subject category, the following variety of locations for publishing synthetic biology knowledge (the most frequent first and the list not being exhaustive) can be seen:

- Biochemistry and molecular biology;
- Biotechnology and applied microbiology;
- Chemistry;
- Life sciences and biomedicine;
- Computer science;

- Mathematical and computational biology;
- Engineering; and
- Cell biology.

Most striking is that, although rooted in molecular biology and biotechnology, synthetic biology is finding readership and entering peer-reviewed press in journals of engineering, mathematics, cell biology and computer science. Synthetic biology has been enabled by the decreasing cost and speed of DNA sequencing resulting in a dramatic increase in the availability of biological building blocks to explore and combine. Over the past ten years, a number of devices have been developed (Drubin et al. 2007).

Interdisciplinarity is a key issue at the level of scientific research where convergence occurs around new combinations. Thus the degree of integration around new combinations is an entrance point for analysing the development of a specific field of technology convergence. To better tailor funding instruments and to understand and provide other incentives for integration in research and in product development, tools and methodologies for measuring integration are important if technology convergence is to be taken, and supported, seriously.

Processes of convergence should be analysed to inform decision-making. Empirical research on processes of techno-scientific convergence and more precise conceptualisations of the processes themselves could improve strategic decisions in R&D policy, help to avoid misallocations of funding and assist in the identification of new fields of convergence (and their trajectories). Indicative of interest in this issue in the social sciences is the recent (2011-2014) funding of two policy focused research projects: the NSF's Science of Science Policy (measuring interdisciplinary research) and the Anglo-French project "Mapping the Dynamics of Emerging Technologies" (which specifically explores the notion of integration and the factors that are important in shaping integration at the research stage and technology production and innovation stage).[20]

ii) Convergence around technology platforms

Clearly seen in the examples of biophotonics and synthetic biology is the emergence of tools and equipment necessary to conduct research, groupings of resources that can be described as *technology platforms* for research. As opposed to production platforms (Gawer and Cusumano 2002), which focus on the standardisation of interfaces to make them compatible with other modules, technological platforms appear as enablers of R&D, as families of technological options and as addressing successive product development.[21]

An important organisational issue for technology convergence is that technology platforms for research are not a collection of equipment alone. They are also protocols, processes and research management mechanisms. Together these enable and constrain actions, dictating the research lines possible (Merz and Biniok 2010). This characteristic relates to the nature of the actual instrument or combination of instruments, what it has been designed for and what can be explored with it, the research protocols and methods that accompany the platforms and associated techniques.

These technology platforms are critical for many research areas that emerge out of the process of convergence. Peerbaye (2004) shows how genomics platforms emerged in R&D institutions and some R&D companies (e.g. micro-arrays) but took on a further feature in France when public financing was made available provided there was some geographical concentration and provisions for access ("*dispositif instrumental partagé"*).

At the level of the organisation of research, recognition of the potential of such platforms incites actions to develop them by research institutions and by governmental agencies. This has been particularly visible in the field of nanotechnology (Robinson et al 2007) e.g. EU-level programmes. It is important to recognise that platforms can provide a nucleating point for research. Often multiple instruments/tools are needed and the various knowledge and skills to use them agglomerate around these platforms. This effect has been particularly visible in the field of nanotechnology (Robinson et al. 2007) and is also seen in both synthetic biology and the recent Human Brain Project (see Box 3).

Box 3. Human Brain Project

The Human Brain Project is one of the two Future and Emerging Technology Projects selected by the European Commission from a shortlist of six projects in January 2013. Receiving EUR 10 billion and planned to last for ten years, the human brain project aims to tackle a key area in Neuroscience - models and simulations of the human brain.

Its emphasis lies in developing six platforms, which will connect up data, models and different actors, to integrate what is already known, identify gaps, coordinate the global research in modelling the human brain and create collaborative opportunities.

The six platforms are the:

Neuroinformatics Platform - combining data and knowledge from neuroscientists around the world and making it available to the scientific community;

Brain Simulation Platform - which integrates neuroinformatics information into computer models and allows for the identification of missing data (which can help direct further research);

High Performance Computing Platform - that aims to provide interactive supercomputing technology for neuroscientists for data-intensive modelling and simulations;

Medical Informatics Platform - that connects clinical data from around the globe;

Neuromorphic Computing Platform - that makes it possible to translate brain models into artificial systems; and

Neurorobotics Platform - to put artificial brain models to work by linking them with robotics.

The project has set itself the goal that, by summer 2015, the six platforms will be ready for use by the community, with a further seven years of operating time.

Further information can be found at: www.humanbrainproject.eu

It is important to recognise that platforms can provide a nucleating point for research. Often multiple instruments/tools are needed and the various knowledge and skills to use them agglomerate around these platforms. This leads us to the third major dynamic involved in convergence at the level of scientific research: agglomeration.

iii) Agglomeration and the emergence of convergence hubs

Converging technologies are multiple combinations of a variety of disciplines, as well as many industries and technology chains, and they will reshape the existing organisational arrangements in R&D. Technological agglomeration[22] (i.e. the co-location of the scientific and technological activities, particularly around technology platforms) supports the development of convergence within the area. It also involves large investments in infrastructure (cf. Genopole (Peerbaye 2004) and the British Synthetic Biology centres).[23] Convergence of nanobiotechnologies and nanobiomaterials, for example, requires bigger and better clean rooms than other sciences (with atomic force microscopes for observation and manipulation at the nanoscale, and e-beam and nano-imprint lithography to make the channels, pores and circuits needed for the research).

Organisationally, agglomeration requires the sharing of facilities, equipment and skilled technicians for these very different technology/research fields (see Box 4). Skilled technicians are a key element in research settings and are often missed out in discussions of technology convergence. They are crucial for research, particularly in complex multidisciplinary environments, and must be factored in when discussing the skills and expertise necessary for converging technologies. It can be envisaged that such technicians have to combine skills and knowledge from multiple fields to be able to construct, test and apply scientific tools, devices and machinery in the laboratory. One example is in biomaterials, where material science meets living materials, creating an overlap of different research protocols and ways of developing and using scientific research equipment. Since such facilities are expensive and take some time to construct, they need high investment (both financially and in training of manpower) over a period of time.[24]

There are two main routes for the organisation of technological agglomeration.[25] There is a bottom up route, where technological opportunities and platforms are engendered by virtue of their being available at the same time (in an “off the shelf” mix of existing instruments and facilities), which allows for various exploitations. The benefits can be recognised, what is happening can be optimised and packaged and can be used elsewhere and at other times. There is also a top down route, where the technological opportunity has to be articulated and designed, which requires a concerted effort from the beginning.

The second route often builds on what has been happening in the first route, in particular when a certain threshold of articulation and stabilisation has been passed. The French public policy that supported the creation of technological platforms within the Genopole programme is an example of such initial bottom-up articulation allowing further steps to be made through a top-down approach (Peerbaye 2004).

Summary: Key characteristics

In convergence in research there is a **co-ordination challenge**. Co-ordination is necessary to create the infrastructures for knowledge creation. Such infrastructures include physical instrumentation and tools and co-ordination policies in research organisations and at a national/regional level. Synthetic biology and biophotonics are examples in which various communities converge to create a new area and require concerted bottom up strategies (for example, in synthetic biology, the BioBricks Foundation) and top-down strategies (for example, the United Kingdom roadmap and dedicated synthetic biology hubs as part of British public research investment). Such challenges are not unique to convergence but are particularly prominent in areas where convergence between previous disparate disciplines occurs.

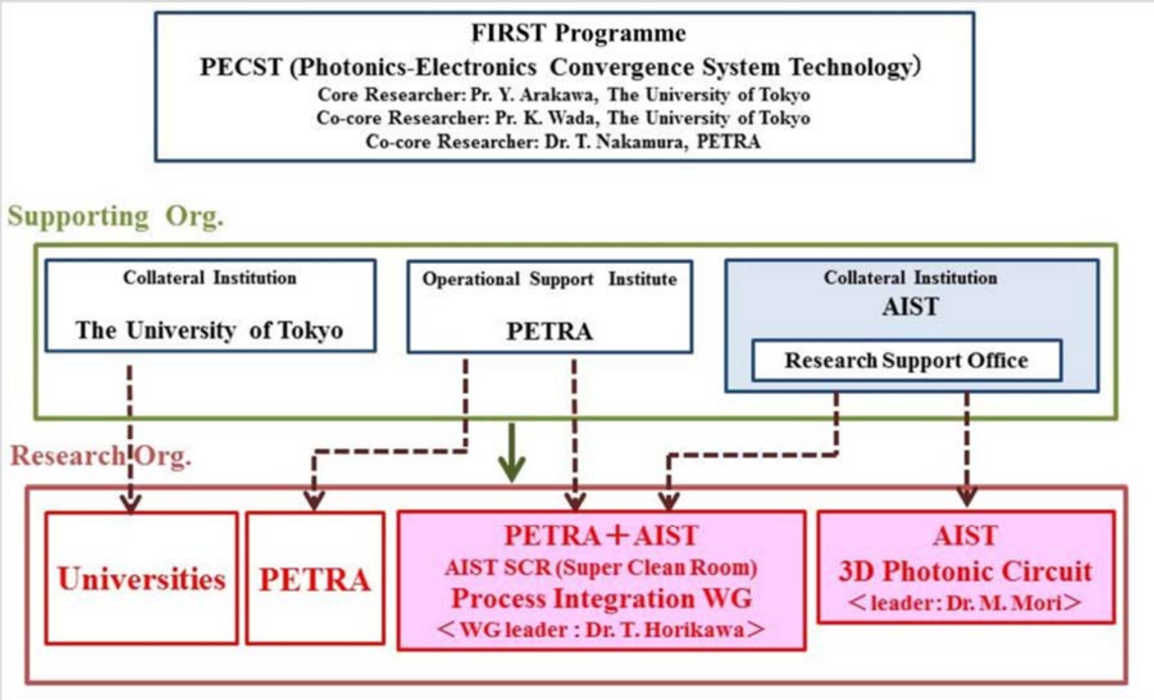
Commercialisation challenges in the use of research output

Commercialisation is defined here as the activities that allow the transition from research to product development. The interface between research and product development is dependent on the commercialisation strategies.[26] Commercialisation strategies therefore enable product development. In this section two elements of commercialisation strategies will be presented that are important for technology convergence: (a) intellectual property management and (b) business models.

Box 4. Photonic-Electronics Convergence

This example outlines the organisational structure of PECST,[27] using the convergence of *Photonics* and *Electronics* to provide the next generation of devices utilising light (photonics).

Photonics is the study and use of light, as information transmission, as energy transmission, etc. It is expected that photonics will improve electronic devices, up to replacing electronics totally (moving from electricity to the use of light).



Source: AIST-PECST, Japan

For this very specific area of technology convergence, the co-ordination of a variety of actors and facilities is necessary. Here you can see the importance of the super-clean room facilities, and the process integration working group located there, which provides the interface between research from the disciplines of electrical engineering, photonics and fabrication scientists (those that fabricate the structures for chip development).

The important element here is that convergence requires organisation and co-ordination of various groups, which may have not worked together before, and the agglomeration around facilities and instrumentation.

Intellectual property management

With a global shift towards commercial use of scientific research (Rip 2002), there is also a growing drive for university research laboratories and publicly-funded research centres to promote the creation of start-up companies and to patent or otherwise commercialise the outputs of research (Miner et al 2012). Given this trend, it is interesting to consider commercialisation strategies in relation to technology convergence.

Returning to the example of synthetic biology, computation and biotechnology play major roles in the story of synthetic biology convergence. Whilst based on biotechnology, synthetic biology demonstrates a rapid discovery process (similar to ICT) and the number of “biological parts” constructed in synthetic biology is ever increasing. It has been noted that such rapid discovery has reached a point where protecting intellectual property through patenting seems an inappropriate means of intellectual capital management (Klein 2012).

Unlike mainstream biotechnology, a key part of the fabric of synthetic biology research is an open access culture and shared accessibility to the data that is being produced in laboratories, something very visible in computational sciences. Indeed, for synthetic biology, since its early stages in the mid-2000s, a large amount of effort has gone into creating a Registry of Standard Biological Parts[28] to facilitate sharing of knowledge. This activity is supported by the iGEM[29] community and the BioBricks foundation[30] and makes it increasingly possible to develop biological assembly standards and open databases (Knight 2003, Anderson et al. 2010).

Thus a culture of openness and sharing (open source), and coupled to it the inappropriateness of patenting as a means of intellectual capital management (Potrykus 2001a, Hopkins et al. 2007, Rai and Boyle 2007), raises the issue of how intellectual property will be owned and shared in its exploitation in product applications. Synthetic biology may follow a similar path to that of the mobile phone industry, where no one firm has the monopoly on intellectual property (patents) and thus, for the industry to flourish, firms have to work together through cross-cutting licences.

Patent thickets could also be an issue. For example, Potrykus (2001b) describes the difficulty in progressing the development of Golden Rice, as the rights to over 60 patents to produce and sell Golden Rice had to be acquired. Synthetic biology innovations could be combinations of hundreds, perhaps thousands, of different building blocks, with a variety of intellectual capital management approaches attached to them (some patented, some open access). This may result in a serious bottleneck to commercialisation in synthetic biology.[31]

Kumar and Rai (2007) have put forward the idea that DNA segments could be thought of as source code for living systems, similar to source code for a computer programme. Thus, akin to software, DNA parts could be covered by copyright.

Business models and alliances

Another element of commercialisation is the actual creation and implementation of a business model.[32] Particularly for high-tech small firms in new and emerging fields, the creation of a business model and the structuring of alliances is a considerable challenge. This is illustrated here through the example of systems-on-a-chip technology, to provide insights into the barriers being faced by those attempting to commercialise new converging technologies in situations where an industry structure is not yet in place.

Example: *Point-of-care diagnostics using lab-on-a-chip technology*

A challenge for firms, particularly high-tech small firms in new and emerging fields, is the creation of an appropriate business model in order for the technology to reach the commercial marketplace. The structuring of the necessary alliances to ensure this can be a considerable challenge. For products to emerge, the development of manufacturing capability, creation and testing of new business models, and development of protocols and standards is needed, all of which requires time and dedicated effort. It also requires co-ordination. New combinations of materials and functionalities that emerge from previously separate industries with different regulatory worlds (for example, biological tissue manufacture) provide considerable challenges for the creation of stable and functioning value chains.

One example of industry that has evolved over the past 50 years is the semiconductor industry. The main engineering and manufacturing tasks involved in creating electronic chips include: integrated circuit design; (physical) manufacturing of integrated circuits; and integration of these circuits into a chip or system (Lee and von Tunzelmann 2005). Originally the whole process was conducted in individual firms; however, the complexity (and the increasingly high cost of production) has meant that the various elements of computer chip development have become organisationally separated. Thus, particularly over the past three decades, there has been a shift in the structure of the industry such that different companies now often work in combination or sequentially to address different parts of the production process (e.g. design houses; mask houses; wafer companies; foundries; back-end processing; and electronic packaging).

Cost and power consumption are key drivers in the digital market, particularly for mobile applications such as phones, tablets and other "smart devices". This has created a pressure on the semiconductor industry to examine possible alternatives to current computer-chips (integrated circuits) with a view to on-chip integration of functional hardware (for example, power management systems, computation, audio/visual, global-positioning, etc.). The pressure to reduce cost and power consumption is expected to continue to change the traditional landscape for chip development towards increased system-level integration in the chip design itself.

Such integration can add value to electronic devices by moving manufacturing from simple integrated circuit chips with limited functionality (where functions are designed around individual circuits to construct a device) to whole systems-on-a-chip with greater functionality (where multiple functions in a device are incorporated at the chip level). Thus the core component of an electronic device moves from a basic integrated circuit to a multifunctional integrated circuit.[33]

The process of technology convergence is leading also to organisational convergence in the manufacturing process, requiring an increasing amount of co-ordination between actors. Joint research and development are necessary, shared between organisations and personnel that were previously separated. This is one example of convergence in manufacturing, where the design and development of devices brings together organisationally separated actors (with their own specific skill sets and knowledge bases) into co-design.

Beyond the challenge of co-ordination, the multi-functionality that is a key part of systems-on-a-chip creates an issue seen elsewhere in the scaling up of production of a new technology or device. The more complex a device, the greater the difficulty in producing technologies that are 100% reliable. This is seen, for example, in sensors for digital cameras.[34]

Complex multi-functionality is seen in lab-on-a-chip point-of-care diagnostics. With their origins in the early 1990s, such diagnostics exploited micro- (and later nano-) technologies to reduce the size of an analytical laboratory to something that could fit into the palm of a hand. The combination of micro/nanotechnologies with nano-biosensors and a variety of functional components, forming hand-held analytical laboratories, was soon linked to the broad vision for point-of-care diagnostics,[35] with immediate reading of a sample (such as blood) enabling rapid detection of a disease or other medical characteristics.

Despite the large investment by some major medical device manufacturing firms and the increase in research into the technologies that could enable lab-on-a-chip devices (van Merkerk and Robinson 2006), industry structures have failed to emerge. This has led to a serious commercialisation challenge, especially for the many start-up companies that were commercialising single components of potential labs-on-a-chip. Box 5 provides a note on a project (Robinson 2010) which explored this in some detail.

Box 5. Lab-on-a-chip innovation models

A project was undertaken to explore the potential industry structures and business models that could be used to stimulate an industry structure and energise the sector. Four innovation models were identified by the representatives of small firms and the researchers participating in a workshop:

1. In-house R&D by a multinational corporation (MNC);
2. Technology development conducted by SMEs but stimulated by an MNC;
3. Start-ups finding opportunities and becoming the integrator for specific applications; and
4. Groups of heterogeneous actors coming together in a cluster to create a modular "tailor-able" platform.

It was agreed by participants that models (3) and (4) were the most likely to succeed since options (1) and (2) had already been tried and had failed (Robinson and Propp 2008).

For model (3), a simplified lab-on-a-chip could be created that would measure one substance (for example, salt in the blood) and could be tailored to other needs (in a product family approach). The focus would be on cheap-to-produce chips and an expensive hand-held reader of the chips. The small start-up would be the driver of the innovation and integrate all the elements.

For model (4), a modular form of a lab-on-a-chip device could be created by a network of small firms. These would enter into strategic alliances with large medical device manufacturers to be able to tailor lab-on-a-chip devices to specific clients. This business model would focus on single, relatively expensive systems for specific clients (without large mass production of the same device).

Six years after the workshop, in 2013, both business models are in evidence and have dealt with convergence in different ways. For model (3), a lithium diagnostic chip is available and produced by Medimate BV36 in the Netherlands for manically-depressed patients. It has been spun out for further applications (such as milk diagnostics in cows).37 For model (4), Lionix BV38 creates tailored lab-on-a-chip devices for clients by mobilising a network of research groups and SME's in individual dedicated projects (for example, the European Space Agency's ExoMars mission39 to detect any signature of life in Martian soil samples). Lionix also combines co-design and modular approaches to the construction of dedicated lab-on-a-chip systems with clients (for example, through its microreactor collaborator Chemtrix, currently in partnership with DSM).40

Also, historically, with the development of integrated circuits, production has traditionally been by trial and selection (i.e. to throw away what does not work, up to 98% at the beginning of the production development process). This created learning curves so that production methods could be improved. To create such learning curves requires there to be sufficient production volume but, in order to have production volume, an agreed process of production (technical standards, assessment criteria) and a product market needs to be in place. This means a co-ordination of the market is needed, and often sits alongside a strategy of producing low-performance, first entry products.

Summary: Key Characteristics

Synthetic biology has been used to show how a field with a number of technology parents combines more than scientific and technical characteristics, requiring the development of intellectual property management cultures and approaches. The sharing and exploitation of knowledge may otherwise be misaligned or be out-dated. Synthetic biology shows that rapid discovery processes and an open access culture of research and knowledge-sharing creates a rapidly expanding field of research, but also creates new challenges for the exploitation and commercialisation of the results. It is clear that traditional patenting strategies for appropriation and potential further exploitation of research results will not suffice (Kumar and Rai 2007).

Synthetic biology has been used as one example, but differences between intellectual property mechanisms may occur elsewhere in technology convergence and thus should be an element of convergence policy. Particularly interesting are novel nanobiomaterials. Often these are multiple use, e.g. as drug delivery particles, as coatings on implants or as elements of sensors in medical diagnostics. Each of these potential uses of nanobiomaterials requires different intellectual property management approaches, given their different industrial application contexts (different product development processes, different development times and different regulatory approaches).

The example of the lab-on-a chip was provided as a small case study to explore the importance of business models and illustrate that business models may have to be invented in a newly converged field. This is not unique to technology convergence but is observed in this area. For converging technologies, the types of actors that will drive commercialisation, be they individual firms or alliances, will need to create business models that can harness the value and create industry structures that allow for product development, manufacturing and market penetration. For areas such as synthetic biology, bio-photonics (section II) and nanobiomaterials and biomedical engineering (see next sub-section), the commercialisation strategies and innovation support policies will be varied and complex. This area will require particular attention if innovation bottlenecks, such as those outlined in the lab-on-a-chip example, are to be avoided (Robinson and Propp 2008).

Product development and manufacturing

Converging technologies have been surrounded by big promises, often called a third industrial revolution, since the birth of the discussions in the early 2000s. This promise provides an incentive to policy actors and industrialists (for example, the NBIC discussions, see Box 1) whilst, at the same time, it can be an obstacle to the realisation of the envisaged benefits because of the diffuse and open-ended nature of the promise. It makes actors uncertain about directions to take and thus creates reluctance to invest in concrete developments and a tendency to adopt wait-and-see strategies.[41]

Though much of the discourse in converging technologies either places an emphasis on the emerging (techno) scientific disciplines or on the exciting possible application to grand societal challenges, very little attention is paid to the industry structures and processes that are required to turn the scientific research into products or large-scale technological systems. If converging technologies are to be taken seriously, it is necessary that there is some understanding of the issues of convergence at the level of manufacturing and product development.

In this sub-section, product development and manufacturing challenges for technology convergence are explored. To keep it concise and relevant to convergence, these issues are described using the example of the value chain for 3-D printing applied to biomedical engineering. The concept of the value chain, in which the material or technological device gains in value at each stage of the chain, is used within the examples to position each product development and manufacturing stage, from the concept to the customer. The value chain concept[42] has been used for three decades now to analyse firms and their respective performances, in order to identify and address performance gaps and challenges (Peppard & Rylander 2006, Porter 2001).

Studies of innovation show that there is a *translation* of promising technoscience into products for society and this translation occurs at the level of industries in particular sectors, with (usually) stabilised configurations of actors involved in adding value in the conversion of the original scientific knowledge into a workable device/product.[43] The value chain model concept is used here as a backdrop against which to explore convergence at the level of technology and product development and to identify policy implications.

Example: *3-D printing applied to biomedical engineering*

Organ and tissue transplantation plays a key role in restoring or enhancing life expectancy. The demand is high, with the Organ Procurement and Transplantation Network[44] registering 112,905 patients awaiting transplantation at the end of 2011 in the United States, whilst only 25,246 transplants were actually conducted (approximately one fifth of the registered demand was provided for). Also, there are challenges in avoiding the body rejecting the biomaterials and organs transplanted into it. The field of tissue-engineering has emerged to tackle this challenge, to create biocompatible materials to transplant into the body and to fill the gap stemming from organ and tissue donation.

To enable advances in tissue engineering, additive manufacturing techniques offer the potential to fabricate tissue (and, potentially, organs). Three-dimensional printing (3-D printing) for biomedical engineering is emerging as an area in which fabrication technology is meeting the life sciences to provide tools to develop increasingly complex structures. Here, tissues and other constructs that will be implanted in the body, or grafted onto the body, are constructed from living tissue into complex shapes and forms. Put another way, the technologies for 3-D printing promise multiple, tailored platforms on which to create biomedical objects, varying from bone up to artificial organs. Existing manufacturing devices have been altered to suit tissue engineering, requiring modifications of temperature, humidity and sterility characteristics (Brown et al. 2011). Some manufacturing devices have recently become commercially available (Wohlers 2010). Already applied in dentistry, this field is true convergence of manufacturing and living matter, with the added characteristic of creating complex products including tailored prosthetics and organs.

However, it is unclear as yet how the technology can be transferred from dentistry to other medical areas, due to the need for many inter-dependent technologies to be combined for the process to succeed (for example, software, standardised biomaterials, digital models of the tissue or organ (Sodian et al. 2002, Sodian et al. 2005), design protocols, etc.). Although research funding for regenerative medicine and tissue engineering has led to the creation of a large number of advanced laboratories and institutes in this field, it is consistently noted that capabilities and funds for scaling-up the manufacturing processes and for clinical trials are lacking (Pangarkar et al. 2010, Mason and Manzotti 2010). In addition, business models are needed (Melchels et al. 2011) that enable the manufacturing of a variety of tissues and the use of these tissues in clinical operations.

Summary: Key Characteristics

If the potential of convergence is to be fully realised, the gap between broad, open-ended promises of applications (and the projections put forward by the world of research) and the realities of technology production and manufacture must be bridged.

What is clear in this and the previous sub-section (on business models and alliances) is that, for products to emerge, manufacturing capability has to be built up, with the creation and testing of new business models and the development of protocols and standards, which will require time and dedicated effort. This is particularly true in the case of new combinations of materials and functionalities from previously separate industries with different regulatory worlds, as new value chains have to be created and made stable. The co-ordination of actors in the creation/transformation of value chains is of critical importance. The development of standards for the manufacturing processes, as well as technical standards for elements of the technology itself, is an important part of the value chain. Lack of co-ordination at this stage can lead to waiting games, situations where there is high promise but little action. Exploration of the possible policy interventions to support innovation stemming from convergence is merited.

Adoption of technologies

When conceptualising convergence as described in this report, both far and near futures can be explored, and indeed can draw on examples that are occurring today. This next chapter examines some of the issues that are involved when converging technologies come (or are expected to come) face-to-face with society.

In line with the overarching goal of this report - focusing attention on specific situations of convergence, their opportunities, challenges and policy implications - the broad promises of converging technology are explored here through concrete examples in the realisation that uptake of a technology takes place in a societal context. For example, the smart phone has entered society and shaped communication and culture. As there are many different fields of technology convergence and a variety of social contexts, societal embedding of converging technologies will be as diverse as the many promised applications. Addressing concrete issues relating to adoption, a single example is presented in detail to provide a flavour of the types of challenges and opportunities in embedding such technologies in society.[45]

After an explanation of the term societal embedding, this section looks at the area of convergence labelled as "Smart Health". Smart health covers a wide range of technology options and potential applications, but here the focus is on the subset of technology applications known as *telemonitoring*. The findings of a multi-stakeholder project[46] investigating relevant barriers are presented as context.

Introduction to societal embedding and technology adoption

Societal embedding is the process of adoption of a new technology into a social setting. Such settings can be healthcare, leisure activities (such as gaming), transportation, food purchase and consumption, communications, etc. It relates to the culture and behaviour of society and how the new technology "fits" into the cultural and behavioural system of society or, alternatively, how society conforms and changes to adopt a new technology option. The latter, which will be referred to here as "societal stretch" (as opposed to *"technology fit"),* has been seen in areas such as mobile telephony and the internet, which have shaped how society views communication in terms of speed and need, and have required new business models (for online services, etc.).

Example: *Home telemonitoring for healthcare*

Historically, the convergence of information and communication technologies has produced a significant number of new technologies, but also new ways of doing business, of trading and of communicating with friends and colleagues. For example, new business models have emerged based on technologies such as smart-phones and tablets.

Assisted living technology is an area of application which combines sensors, devices and communication systems to provide aid to a person in their own home. The potential gain from using informatics to detect whether the health of a person is in decline, outside of a hospital setting, has been recognised as a key area, especially related to the demands of an ageing population where increased prevalence of certain ailments will require new healthcare models.

Telemonitoring is "*an automated process for the transmission of data on a patient's health status from home to the respective health care setting*" (Paré et al. 2007) i.e. the use of information and communication technologies (ICTs) for the delivery of many types of care in a home setting with the aim of supporting independent living. There are many telemonitoring applications in development and in use today, with varying degrees of automation.

However, despite significant investment, efforts so far have not led to convincing evidence that informatics interventions are cost-effective (Gaikwad and Warren 2009, Vitacca et al. 2009). Indeed, the industry-focused consultancy Gartner Inc. places remote telemonitoring in the ‘trough of disillusionment’ at the present time (Edwards et al. 2009).

To understand more fully why this area was not successfully translating into healthcare practices, an exploratory study was set up by Cardiff University. The aim was to determine a research agenda for the development of effective and sustainable community-based early detection methods for problems commonly experienced by patients suffering from, for example, heart failure or diabetes. In the study, a number of stakeholders were brought together in a collective exercise to explore the technological and societal embedding challenges for telemonitoring (as a subset of Smart Health).

A key component of this activity was a one-day workshop, which brought together technology developers and researchers, carers, health care professionals and service planners and managers from the United Kingdom’s National Health Service.[47] One output was Figure 1 below, which gives an indication of the challenges identified by the participants and the organisers of the study. The nature of the challenges relating to embedding new technologies into everyday working practice varies across the health sector according to the setting (domestic, delivery, management, policy and legislative) and these have been distributed in the diagram to reflect this. For clarity in the visualisation, two major challenge categories are differentiated: “barriers to progress” in desirable R&D trajectories of development and “supply industry challenges” respectively.

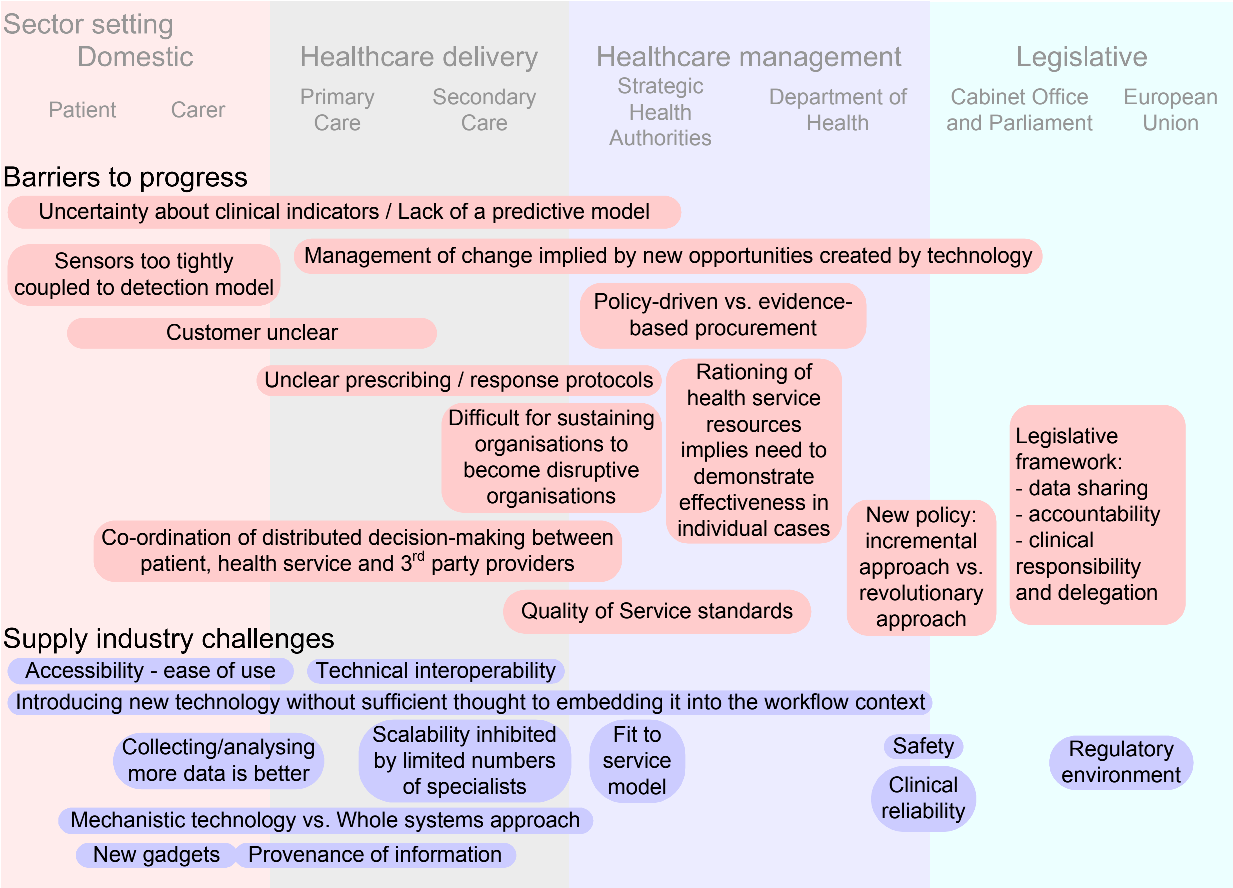
Evident here are specific barriers in research and development relating to the embedding of the technology into healthcare systems. These were seen to arise from a lack of clear understanding about: which clinical indicators are the most significant, sensitive and useful indicators of impending health decline; the lack of a usable predictive model to make a judgement of what is a decline in health,[48] and the issue of precisely who the “customer” is in the implementation of early detection approaches (e.g. the patient or the health service provider) and to whom is the technology being marketed.

Similarly, issues relating to the way in which the technology has been designed to restrict its use and uptake in areas not defined by the technology developers were visible in the study. For example, the problem of sensors being too tightly coupled to specific detection models (sensors designed for a specific purpose limit the usefulness of such technologies for those with complex health issues (or co-morbidities)).

From the medical side, the lack of clarity about the clinical decision-making and response protocols inhibits widespread adoption of such technologies. Thus, clinicians need to be actively involved for the adoption of telemonitoring to be successful.

Other barriers observed included the link up with national systems of innovation and systems of healthcare (for example, the issue of where decision-making responsibility lies when service is outsourced or spread across multiple providers). Consumer-led or population-level innovation implies disruption, and large organisations such as the United Kingdom’s National Health Service (NHS) find it particularly hard to accommodate disruptive change as they are more suited to sustaining a particular type and level of service. They find it hard to be agile and to adapt to new ways of working, which are required for the embedding of new technology options (Hardisty et al. 2011), and are equipped to realise the benefits of a well-understood and stable approach, rather than to risk the move to a new option. The difficulties of adapting policy and legislative frameworks at a pace sufficiently fast to accommodate possibilities arising from technology innovation were seen as key factors for the deployment of telemonitoring.

Figure 1. Challenges associated with embedding technologies into healthcare settings



Source: Adapted from Hardisty A. (2010)

In large organisations, special projects may generate local enthusiasm and time-limited support. However, in the case of the NHS and Social Services in the United Kingdom there is no real evidence that the systemic change needed to normalise[49] a new monitoring service has been achieved. For telemonitoring technologies, a fundamental lack of clarity was observed regarding the location of decision-making responsibility when the service spread across multiple providers. This issue has not been addressed in work to date and may require changes in how services are designed and managed. It has implications for existing medico-legal frameworks. There is also a lack of comfort and trust that stems from the uncertainty about accountability for taking actions as well as from deficits of knowledge and understanding across the care systems.

The supply industry faces multiple challenges in the design and marketing of telemonitoring technologies. Population-level scalability (that is the widespread uptake of the technology system) is limited by the constraints of the existing skills base: there are, as yet, insufficient numbers of appropriately trained professionals – both clinicians and technicians.[50] Other key issues included the necessary development of service models, identifying how to embed new technologies into working practices and questions of safety and clinical reliability.

On the positive side (and not depicted in the figure), innovation in technology, and consequential service change, brings about new opportunities. Increasingly knowledgeable and empowered patients can contribute their interest in and shared ownership of care and the associated records. Availability of new data and clear interpretational information can be a powerful mechanism for explaining a (distressing or serious) situation to a patient. The trend towards increasing involvement of the private sector in the delivery of healthcare creates business opportunities around large-scale, population-level early detection services.

Summary: Key Characteristics

The section presented the example of telemonitoring as an area of converging technology that has been struggling with adoption over the past decade. The technology components are available but putting them into a workable and functioning configuration for broader application to healthcare remains a challenge.

In this example, issues related to the decision-making structures (when a certain indicator of an ailment is detected), and the medico-legal framework that relates to decisions and actions based on the telemonitoring system, show some of the important elements that should be considered in putting this converging technology to work. The organisational structure, healthcare policy, insurance structures, etc. all play important roles here.

A large number of societal embedding issues for telemonitoring are apparent and a further step can be taken to explore similar tensions and opportunities for other areas in “smart health” which itself is a promising area of technology convergence.

Beyond the case of telemonitoring, if converging technologies are to fulfil the promise of contributing to grand societal challenges (section I and II), then societal embedding and adoption are critical elements if the benefits of convergence research are to be realised. An entrance point here could be support for exploring future use scenarios and societal embedment/adoption pathways as an integral part of convergence research, especially in areas of technology convergence that are linked closely to a sector or social system (such as food production, healthcare, transport, etc.).

Scholars of science and technology studies have focused a lot of attention on the dynamics of the uptake and use of new technologies. For example, studies of strategic niche management have looked at how new technologies have fitted into incumbent industries and user practices, or have shaped them (van de Poel 1998, Elzen et al. 2004). Support systems such as SOCROBUST (Laredo et al. 2002) to aid firms to explore future embedding scenarios have been developed which make use of such insights.

Societal studies and debate

Much of the early days of NBIC discussions around the globe focused on human enhancement through improving human performances (both individual and social).[51] The healthcare promise of providing implants, such as deep-brain stimulators, prosthetic limbs and artificial organs, was often blended with the idea of improving performance of clinically healthy persons to move beyond what is classed as a healthy human (Swierstra et al. 2009).

In the second half of the 2000s, promises of converging technology began to broaden. The notions of human enhancement became more articulated and other technologies emerged (for example, neurotechnology, such as brain-stimulation technology (deep-brain implants), remote monitoring for healthcare (telemonitoring) and the creation of new forms of life at the level of cells (synthetic biology)).[52] Projects such as CONTECS[53] (2009) and Making Perfect Life[54] (Van Est and Stemerding 2012) began to focus on specific contexts. For example, Making Perfect Life[55] looked at a broadened notion of bioengineering and explored ethical and societal issues in four sub-groupings of bioengineering fields.

Limited or no societal debate is observed on “Converging Technology” in an examination, a dedicated activity for this report, including the analyses of projects discussed already, NBIC2, CONTECS and Making Perfect Life, all three being recent activities with an emphasis on societal and ethical issues and governance. Also, the activity included a search through the peer-reviewed journal database using the Google Scholar[56] academic search engine. An additional and more dedicated search through specific journals enabled any references or descriptions of converging technology dedicated engagement activities to be found. Journals such as NanoEthics (Springer press), Public Understanding of Science (Sage publishing), Social Studies of Science (Sage publishing), in which social engagement on new and emerging science and technologies are reported and detailed, were studied.

It is not surprising that little dedicated debate and engagement is focused on NBIC and converging technologies *per se*. In the early days, NBIC and converging technologies concentrated on human enhancement and thus ethical and societal discourse, predominantly in the world of academic scholars, related mainly to human enhancement. With the broadened description of convergence (see section II), instances of convergence help to identify the challenges, issues and opportunities of a specific situation of convergence in a particular context. For example, in a special issue of NanoEthics in 2009, reflections on societal and ethical issues focused on particular application areas (see Box 6 below).

Box 6. Special Issue on Converging Technologies in the Journal of NanoEthics

NanoEthics Volume 3, Issue 3, December 2009. http://link.springer.com/journal/11569/3/3/page/1

Below are listed the articles in this issue relating to converging technologies. What is visible here is that although transhumanism as an issue remains dominant, discussions and explorations of the ethical and societal aspects of converging technologies are explored through particular application contexts. For example, ambient intelligence, molecular medicine, brain-machine interfacing etc. The articles are listed below to illustrate this focus.

Editorial:

Boenink, M., “Tensions and Opportunities in Convergence: Shifting Concepts of Disease in Emerging Molecular Medicine”.

Schermer, M., “The Mind and the Machine. On the Conceptual and Moral Implications of Brain-Machine Interaction”.

Tsjalling, S., M. Boenink, B. Walhout, R. Van Est, “Converging Technologies, Shifting Boundaries”.

Tsjalling, S., M. Boenink, R. Van Est, “Taking Care of the Symbolic Order. How Converging Technologies Challenge our Concepts”.

van den Belt, H., “ Playing God in Frankenstein’s Footsteps: Synthetic Biology and the Meaning of Life”

Verbeek , P-P., “Ambient Intelligence and Persuasive Technology: The Blurring Boundaries Between Human and Technology”.

Summary: Key Characteristics

A number of studies have looked into potential societal impacts, for example the CONTECS project and Making Better Life (Van Est and Stemerding, 2012), the latter exploring convergence in particular areas of the bioengineering field.[57]

NBIC and Converging Technology have been the focus of limited public debate. A reason offered, as indicated by the shift in ethical and societal scholarly discourse, is that it is the discussion of socio-economic impacts that is usually the driving force behind public engagement activities. Impact issues include those such as privacy, equality, wealth distribution, impact on particular communities, distribution of resources, and potential health and environmental risks.

IV. WHAT ARE THE IMPLICATIONS OF CONVERGENCE?

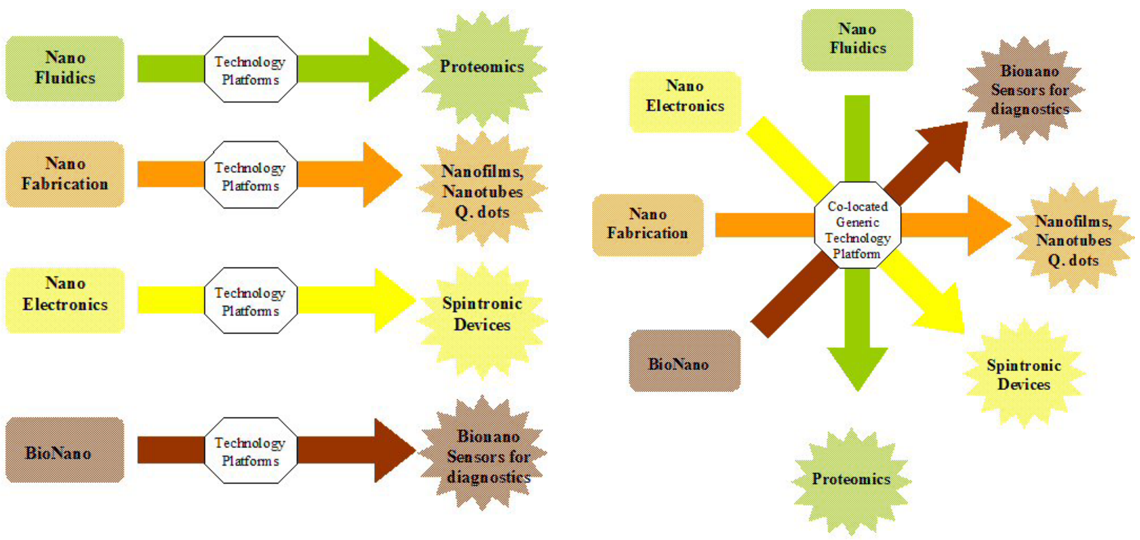
From the start, this report has moved away from the debate about "Converging Technology" to focus on real-world examples. Having examined some of these, with their challenges and opportunities, this chapter focuses on the question; "*what may be the policy implications?*"

The following discussion highlights the most relevant factors identified for (a) scientific research; (b) innovation and product development; and (c) socio-economic impacts.

a) Issues influencing convergence in scientific research

Convergence around technology platforms (instrumentation) is one way in which disparate disciplines collaborate and integrate. Many areas of convergence at the level of research occur around such platforms, and their construction and use can act to bind communities (see Figure 2). Such platforms are difficult to map, tools and instruments are rarely the focus of research articles in peer-reviewed journals and many do not have wider commercial application, acting as a disincentive to patent. However, such platforms could be a major component of convergence and a mechanism to monitor and map these elements may be useful in guiding policy decisions.

Figure 2. Simple schematic of convergence of disciplines based on technology platforms and their agglomeration



Source: Robinson, Rip and Delemarle (2014 forthcoming)

Therefore, further investigation into the forms and functions of these platforms and research orientations could be useful, particularly in regional policy where science/innovation districts are in place or in development. Ways of evaluating successful integration through these institutions with a view to convergence may also be useful. Similar work has been conducted already for nanotechnologies (where convergence was evident). The PRIME Nanodistrict project[58] provided examples of active co-ordination of subdomains of nanotechnologies through the agglomeration of technology platforms and instrumentation facilities which then became central hubs for convergence between disciplines at the nanoscale.

b) Issues influencing innovation and product development

For innovation to succeed, alignments and information exchange between research, industry and third parties (such as regulators and investors) is necessary. This is increasingly recognised in research funding programmes and in the organisation of research and science districts.

Challenges related to value chains for converging technologies were described above, including the reconfiguration of an existing value chain (systems-on-a-chip) and the creation of new value chains and business models (3D printing applied to biomedical applications).

What is clear is that for products to emerge, the building up of manufacturing capability, creation and testing of new business models and development of protocols and standards, requires time and dedicated effort. This is particularly visible when new combinations of materials and functionalities from previously separate industries (and different regulatory regimes) come together, providing considerable challenges for creating stable and functioning value chains. The co-ordination of actors in the creation/transformation of value chains is of critical importance, to develop standards for processes of manufacture as well as technical standards for elements of the technology itself.

The pressures and incentives to link research to innovation, and the high level of uncertainty associated with convergence, has led to the establishment of a large number of future-oriented co-ordinating activities. In the past eight years, anticipatory forums have emerged that attempt to align actors to create value chains, amidst the high uncertainty of converging technologies and the diversity of their forms and applications. In the case of nanotechnology, many of the projects have been led and funded through research funding programmes. Looking at Europe, one platform is the European Technology Platform for Nanomedicine, which is a public research and private R&D network which determines strategic agendas (formalised expectations of the community) and creates roadmaps. Articulating futures and stabilising expectations has been the aim and has led to some success; however, interaction with the potential users of the nanomedicines has been not been a visible element of this European Technology Platform.

A focus on the users has been the aim of CLINAM,[59] an annual conference where the medical community (doctors and medical researchers) congregate to explore the current state of the art of nanomedicine-related research and to speculate about potential and desirable futures. NanoBioRAISE was a European project aimed at articulating potential governance and ethical challenges for nanomedicine in order to provide intelligence for both governance actors and innovation actors alike. Looking at the whole value chain, MEDITRANS (Parandian et al. 2012) focuses on translating R&D on nanotechnology into medical value chains. Comprised of a diverse set of firms (including large pharmaceutical firms), the project assesses expectations and seeks to identify the most promising innovation pathways (and these act as a guide to align value chains from lab-to-clinic).

Innovation through technology convergence requires active collaboration between multiple disciplines (see section II) and multiple industrial structures (see section III) and can take place throughout the innovation value chain. Such collaboration is necessary to create the technology-production-infrastructure that will enable the manufacture of new convergence enabled products. Also, the skills necessary in both research and development become a pressing issue in many fields of convergence. Deeper investigation into the requirements of an emerging technology production infrastructure could be helpful in providing the information needed to target support policies for convergence innovation.

c) Issues influencing socio-economic impact

There is a need to anticipate the potential impacts of converging technologies and develop governance approaches for areas where activities are underway. This would enable those technologies which would provide benefit to be pursued, whilst constraining those that may cause harm. But the potential breakthrough nature of converging technologies, like synthetic biology and nanobiomaterials, as enablers of radically new applications may mean a complex change in industry structures, markets and user cultures (cf. the effect of the smart phone, for instance). This is visible already in some of the examples described in this report (nanobiomaterials) and in a sister report (OECD 2014) focusing on nanotechnology enabled convergence (the example there is nanomedicine). In both cases, there is a collision of regulatory and governance structures.

Deeper investigation of the emergence and workings of governance structures in the evolution of new technological fields would be useful here, but would be dependent on particular instances of convergence, for example in healthcare, in communication, in sustainable energy etc.

Section III-4 presented an example drawn from the world of Smart Health, illustrating the complexities of societal embedding that a relatively uncontroversial and stable technology option (telemonitoring) has had to face. It can be envisaged that with fields such as 3-D printing of organs, synthetic biology, biophotonics and edible and biodegrable nanomaterials, different issues will become important to resolve if the technology applications are to be adopted into society and used.

Thus, “Converging Technology” is not a coherent field of technology emergence, but varied, heterogeneous and rich (thus, defining the societal consequences of “Converging Technology” would be unproductive). The issues and dynamics described in this report provide a first step towards creating a description of “convergence” that will support this.

In addition, support systems to control the speculation of emerging fields of convergence are needed, and there are some approaches already available (developed for nanotechnology) that could be further tailored to suit the needs of convergence.[60]

Given the emphasis on socio-economic impacts of converging technologies, there is a need to trace and evaluate them. Indeed, the OECD is active in this area, for example through a large meeting with the US National Nanotechnology Initiative on indicators of socio-economic impacts (Washington, DC on March 27-28, 2012). What was clear from the discussions in that forum was that such attempts are fraught with difficulties, because there is rarely a linear causal relationship between an enabling technology and impact. Impacts are heterogeneous, distributed across R&D hubs and value chains, and more often than not it is difficult to disentangle the web of activities and attribute an impact to a single point source. This is a generally recognised issue, but still there is a need for indicators to be developed.

One approach which tackles this, and that is described in brief in the sister paper to this report that focuses on nanotechnology, is the exploration of different types of impact pathways. Depending on the nature of the technology and the domain context, there are patterns in impacts, and indications of socio-economic impacts could be derived from that. Little work has been conducted to-date on this, and thus there is an opportunity to direct some attention to this real and present challenge.

V. CONCLUDING REMARKS

When the broad "Converging Technology" debate is examined in more detail, it is seen that new communities are emerging around new combinations, and there are patterns that can be traced. Not *a priori*, but there *are* tools to trace these patterns which take into account the specifics. A number of fields where convergence is occurring are particularly promising, in that there are high hopes about the transformative power of these fields, and the examples provided in this report, such as synthetic biology and biomedical manufacturing, were chosen to reflect this. In conclusion, the umbrella term of "Converging Technology" provides a unifying broad vision of a large-scale transformative technology wave, but when one looks at the nature of convergence, the characteristics are wide, varied and rich.

Policy makers cannot afford to neglect the promise of converging technologies, even if the rhetoric surrounding them is frequently hyperbolic in nature. The challenge is what to do. Apart from the specifics of the various cases that have to be addressed, two main approaches were identified in this report. First, the on-going dynamics of converging technologies are largely outside the scope of government intervention, but governments may diagnose what is going on (this is where tools come in) and on that basis define interventions which modulate on-going developments and nudge them in better directions. Second, *instances of convergence* rather than *converging technologies* should be the entry point, and this requires consideration of further levels of convergence than the emergence of exciting new fields like synthetic biology and smart health.

NOTES

1 The term NBIC relates to convergence of Nanotechnology, Biotechnology, Information and communication technology (ICT) and Cognitive sciences.

2 The technological augmentation of human capabilities and modification of the human body and intellect.

3 UK Synthetic Biology Roadmap (www.rcuk.ac.uk/documents/publications/SyntheticBiologyRoadmap.pdf)

4 For example, the recent announcement of the British Government's Business Secretary, Vince Cable, concerning the creation of an Innovation and Knowledge Centre in Synthetic Biology (www.bbsrc.ac.uk/news/policy/2012/120911-n-synth-bio-centre-welcomed.aspx)

5 The recently announced European Flagship Project Human Brain Project is an example of large investment in areas of convergence (www.humanbrainproject.eu), as discussed later in this report.

6 For example, projects like COTEC, which concluded in October 2012, focused on converging technologies for manufacturing (www.fp7-cotech.eu). This project will be discussed later in the section covering Technology and Product Development.

7 AIST Information & Communication Technology, Biotechnology, Energy & Environment Technologies, and Converging Technologies (IBEC) Innovation Platform:www.open-innovation.jp/ibec/

8 To date, "NBIC" and "Converging Technology" are used interchangeably

9 http://cordis.europa.eu/documents/documentlibrary/124377001EN6.pdf

10 Although converging technologies have been argued to have occurred before, in the 2000s the concept placed at its core the combination, fusion and synergies between different fields of research.

11 Fuller, S., Luce, J., Giorgi, L., Sharan, Y., Soffer, T., Bechmann, G., Büscher, C., Batorowicz, B., Żółtowski, T., Pieszyńska-Golińska, M., Tzeng, A. and Brillet, E. (2008). Deliverable 1. Research trajectories and institutional settings of new converging. Part of European project KNOWLEDGE NBIC. Knowledge Politics and New Converging Technologies: A Social Science Perspective. http://ec.europa.eu/research/social-sciences/projects/180_en.html

12 Here, converging technologies was linked to third generation – integrated nanosystems (systems of nanosystems). See www.irgc.org

13 http://ec.europa.eu/bepa/european-group-ethics/index_en.htm

14 http://wtec.org/NBIC2/

15 For example, the presentation by Mike Roco at the recent NBIC 2 meeting in Belgium, he described convergence in the form of platforms at multiple scales. 1) Foundational Tools (NBIC+), 2) Earth Scale platform (Earth systems), 3) Human Scale Platforms (social-infrastructural systems such as Mega cities); and 4) Societal-Scale Platforms (how societies behave). M. Roco (2012) Methods and global investments for converging technologies. Converging Technologies for Societal Benefit, Leuven, September 20, 2012.

16 Parallels can be drawn with other areas of scientific discovery that have been accelerated by convergence. For example, the development of x-ray crystallography during the 1940s which triggered a large scale move of physicists and chemists into the field of biology, leading to revolutions in molecular biology (which lead to the discovery of DNA).

17 www.uniraj.ac.in/cct/

18 For information on biophotonics, see the US NSF Centre for Biophotonics Science and Technology (CBST) at http://cbst.ucdavis.edu/about. Also, details of biophotonics convergence are provided by the Korean Biophotonics and Nanoengineering Laboratory at http://binel.snu.ac.kr/Research.

19 One of the longer standing events for presenting results and sharing experiences is the BioBricks Foundation Synthetic Biology Conference Series. http://sb6.biobricks.org/about/

20 Both projects are summarised briefly in the following website: www.interdisciplinaryscience.net

21 A sector can then be viewed not in terms of a dominant design and related industry structures, but as a patchwork of technology platforms and related co-ordination, up to aggregation.

22 Technological Agglomeration is the geographic co-location of different scientific and technological fields around such platforms. Technological opportunities as well as requirements on further technological development (e.g. a next generation of chips) stimulate linkages and co-ordination amongst different fields. This creates cumulative advantages for clusters in which a wide range of scientific areas are explored. Thus, there is a technological driver in the agglomeration of actors and activities in a geographical region that builds on clustering/proximity. Technological agglomeration is a general phenomenon, but it is particularly visible in newly emerging/converging science and technologies.

23 For example, the recent announcement concerning the creation of an Innovation and Knowledge Centre in Synthetic Biology (www.bbsrc.ac.uk/news/policy/2012/120911-n-synth-bio-centre-welcomed.aspx).

24 An example would be the state-of-the art Extreme Ultra-Violet lithography platform which is priced in the order of USD 40 million.

25 Other routes in between may be found, a mix of the two main routes.

26 In this report, commercialisation has been separated out from product-development because of the nature of the issues and activities.

27 Photonics-Electronics Convergence System Technology programme http://pecst-aist.jp/index-en.htm and www.pecst.org/brochure2011.pdf

28 http://partsregistry.org/Main_Page

29 http://igem.org/Main_Page

30 http://biobricks.org/

31 It could be argued that this can be applied more widely to converging technologies where a vast array of disciplines and knowledge come together.

32 A business model is the organisation of value creation by a producing firm. This includes the creation of product, the alliances necessary to produce and distribute the revenue etc.

33 This report will not go into detail on systems-on-a-chip-technology or the closely related networks-on-a-chip technology. However for more information, this article from October 2012 is suggested: www.eetimes.com/design/power-management-design/4397940/System-on-Chip-technology-comes-of-age

34 For single lens reflex cameras (Digital SLRs) the number of active pixel sensors varies and often the camera sensors are separated into high quality and low quality, with the price of the cameras adjusted accordingly.

35 This became a promise-icon which arguably substantially hindered lab-on-a-chip innovation at the turn of the millennium.

36 www.medimate.com/index_uk.html

37 http://blue4green.com/en/about-us/

38 www.lionixbv.com/applications/app-lab-on-a-chip.html

39 www.lionixbv.nl/applications/app-lab-on-a-chip.html

40 www.chemtrix.com/

41 A special issue of the journal Technology Analysis and Strategic Management was devoted to this pattern in technological innovation. See Robinson et al. 2012 for an overview of the dynamics of innovation impasse and waiting games.

42 A value chain is 'the series of activities required to produce and deliver a product or service' (Porter 2001). The chain is constituted around the activities required to produce it, from raw materials to the ultimate consumption of the finished product. Elements of a value chain have been described in terms of comprising suppliers, manufacturers, distributors, and consumers. For example, one of the better-researched chains - the wireless communication (mobile phone) chain - includes equipment companies; infrastructure companies/network operators; Steinbock 2003), who interact with a multitude of specialised companies (software intermediaries; financial intermediaries; content providers; resellers (Peppard and Rylander 2006) which in turn engage with the end customer (Li and Whalley 2002). Scanlon (2009) includes a 'reverse supply chain', which re-connects the user with the original equipment manufacturer whenever phones are returned for repair or disposal.

43 That can be embedded in society.

44 http://optn.transplant.hrsa.gov

45 The form of societal embedding and adoption of new technologies is varied and context dependent. An exhaustive analysis is beyond the scope of this report. Thus a single example has been chosen to provide enough detail to illustrate the types of issues, opportunities and challenges that may have policy implications.

46 The full project is presented in two publications (Hardisty et al 2011 and Elwyn et al. 2012). The data presented here comes from a workshop co-organised and animated by Alex Hardisty, Douglas K. R. Robinson and Carl May. See the publications for further details.

47 The workshop was facilitated by Alex Hardisty with assistance throughout from Douglas Robinson (TEQNODE Limited) and Carl May (University of Newcastle).

48 Note also that notions of what is a healthy person, especially when considering the ageing population and the recently announced economic needs of an active ageing population, also form part of the considerations.

49 That is to embed a technology and the associated skills, training and other knowledge required to make it work.

50 Technicians are often overlooked in both R&D and in the operation of new technologies in practical settings, such as hospitals. This is a key factor which will become ever more pressing if converging technologies provide ever more sophisticated multi-functional tools for healthcare; the technicians have to be available to operate the tools and machinery.

51 In fact they continue to this day, see Ferrari et al. 2012.

52 Incidentally all of these three technology promises have come to pass, though many of them still have struggles fitting with or stretching society, such as telemonitoring.

53 A European Sixth Framework Programme project created to form a social science agenda for converging technologies.

54 It should be noted that there are some overlaps in the participants in these two activities.

55 The final report was made publicly available in December 2012.

56 www.scholar.google.com

57 While there is limited or no societal debate on "converging technology", there are some engagement exercises involving specific areas of convergence, such as synthetic biology (Bhattachary et al. 2010, Philp et al. 2013).

58 www.prime-noe.org/nanodistricts.html

59 www.clinam.org

60 For example the variety of tools developed for constructive technology assessment (CTA) of nanotechnologies described in section III. Also projects such as Socrobust (Larédo et al. 2002) provide a starting point. Socrobust was an attempt at creating anticipatory management and assessment tools for the analysis and improvement of the societal embedding of innovations located at the level of project managers in the firm.

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