ECONOMICS

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DTI OCCASIONAL PAPER NO. 8

Innovation Trends: Prioritising Emerging Technologies Shaping the UK to 2017

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APRIL 2007

Contents

Abstract

This report sets out the background to the prioritisation process for policies related to emerging technologies that will shape the UK to 2017. We introduce a set of concepts about technologies that are likely to have a major impact on the UK economy, society or culture in the near future. We distinguish among different forms of disruptions and transformations and show how the concept of "general purpose technologies" can be applied to understand the likely large-scale effects of some technologies. These concepts feed into a discussion of likely rates of technological innovation and of the differing rates of diffusion over the coming period and the effect that could have on prioritisation.

1. Introduction

This report was commissioned by the Horizon Scanning Centre[1] within the Foresight Directorate of the Office of Science and Innovation. Its purpose is to introduce the application of the concept of technological change and describe the factors affecting the introduction, initial adoption and subsequent spread of new technologies, to describe how they are introduced, the changing timescales over which the processes occur and to present some views on the character of technological innovation, in order to:

1. Assist in the process of identifying and defining criteria to prioritise technologies; and

2. Inform non-technologists about these issues.

We do this by reflecting on the general concept of disruptive technologies and then distinguish it from the role of technological change in the major discontinuities that transform social and economic relations. We extend the utility of this approach by applying the concept of "general purpose technologies" [GPTs]. We then consider the application of stages of introduction, adoption and dissemination of selected critical technologies over the period 2007-2017, and their policy implications.

Flintstones vs Jetsons

When the animators Hanna-Barbera created the *Flintstones* they projected two lower middle class families into a stone-age American suburb, complete with stereotypical interpersonal relations, consumer habits and even the infrastructure of the newly-built suburbs of the 1950s. A marvellous commercial success, the *Flintstones* were easily morphed into the *Jetsons*, more or less the same families projected into a future of spaceships and automatic appliances (almost identical to much later images of "intelligent homes"). As with most clever visions of the future, Hanna-Barbera's images were of contemporary life with only superficial trappings of a romanticized stone-age past and of a spaced-out future.

As with all images of the future, these cartoons project our fears and hopes of the future onto the idealized landscape of a familiar present, only taking into account the extension of trends that evoke themes that we might choose to emphasise. Those themes are typically utopian, dystopian, or life as it is, only more technologically dependent. In the case of the *Flintstones* and *Jetsons*, they left alone most of the really interesting things: social and interpersonal life; spatial and temporal relations (even though the *Jetsons* used rockets they still travelled around the strict equivalent of their own neighbourhood); and work. They only tinkered with shelter, sustenance and security (everybody was always

1. The Office of Science and Innovation Horizon Scanning Centre (HSC) works to inform departmental and cross-departmental priority setting, and to facilitate horizon scanning capacity building being carried out by others inside government. This paper is a contribution to the HSC's project to identify the impact of disruptive technologies most likely to affect wealth creation, challenge society, or change the way in which public services can be delivered, in order to inform Government plans and spending priorities for 10 years from 2007/2008.

safe, although they occasionally crashed their stone-wheel cars and personal rockets). Where their imagination ranged more widely was with communication (where the *Flintstones* used a squawking bird for a factory whistle and the *Jetsons* used wrist-watch telephones – an image already common in futuristic comics of the 1920s like *Dick Tracey*). They probably meant to portray significant differences with regard to food, although that was less well thought out since the *Flintstones* merely ate huge joints of meat and the *Jetsons* ate processed gloop excreted from kitchen machines. They also had some imaginative notions of play, but both families had leisure time (and tastes) typical of aspirations of the American lower middle-class suburbanites they were.[2]

The sense that is conveyed about food of the future does allow us to see how extrapolation might work. Appliance-dependent, rocketing *Jetsons* did “enjoy” transformed food, perhaps not so different from the then familiar canned food, but evoking more recent images of freeze dried, microwavable, or half-baked processed foods. The content of that food, we can easily imagine, was more adapted to the new environment and met personal needs better. We can also imagine that it was produced with technologies such as genetic modification, but those mechanisms were not conceived by Hanna-Barbera. Whereas they captured the idea of the transformation of food, they did not imagine the associated social and commercial context brought about by fast food take-aways and eating at shopping malls.[3]

There is no standard terminology for this subject and it has always been marred by the rhetoric of zealots, enthusiasts, dreamers and those who just don’t know enough about trends and the past to realise where their current experiences are historically unique (or not). Our concern is to see how we can better think through what changes and what does not, and offer some ways to order our thinking about the basic dimensions of technical change. These include the temporal character describing the speed and sequencing of the introduction, adoption and spread of technologies. It includes a way of thinking about the scale, scope and pervasiveness of changes. It also includes guidelines on how we, those of us concerned with British conditions and with a limited range of specific policy instruments, can order our priorities and plan.

2. At the same time on television, Jackie Gleason in “The Honeymooners” portrayed a man just like Fred Flintstone in a filmed (rather than animated) programme where all these elements were almost identical, except that it was set firmly in the present (circa 1960) and in a New York-like metropolis. Taken together, the past, the present and the future all looked exactly the same except for the distinction between suburban and urban life (at that early date suburban life was not yet portrayed other than in cartoons).

3. There is a close analogy with the portrayal of future transport where flying in airplanes and floating in the air are portrayed, but the conveyances are propeller-driven or dirigibles such as those seen in Fritz Lange’s 1925/26 film, *Metropolis*.

2. Disruptive technologies and disjunctures

One of the most influential approaches to the problem of coping with innovation stems from studies by Harvard Business School professor Clayton Christensen, whose 1997 book, *The Innovators' Dilemma* brought the term "disruptive technologies" into common parlance. Based on studies in the history of technology, that book described how being good at innovation, manufacturing top quality products, and anticipating customers' expectations is not nearly enough in some cases. To take his central example, the computer hard disk drive was being rapidly improved throughout the 1980s by a group of aggressively competing companies which effectively brought prices down while increasing the storage capacity of the drives, improving processing speed, and otherwise keeping ahead. Their business model was overturned in a short period by a few peripheral competitors whose products had less storage capacity and slower processing speeds. They were even more expensive and made less profits for their manufacturers. The advantages they had were in size, weight and energy consumption – three criteria that had not figured as priorities for mainstream manufacturers. The catch, we all now recognize, is that PCs were becoming small and the portable computer market was beginning to boom. The new competitive criteria rapidly became miniaturisation and low battery consumption.

Generalising from this and similar cases of disruption of leading firms, big sub-sectors of industries, and even industries themselves forces us to think about where innovations come from and how we can recognise them at an early stage. Christensen extends his thinking to the surprises and disadvantages that emerge from the dependence that most companies have on customers and investors for both funding and ideas of what the market will want. He also makes us reconsider how we analyse markets and points out that markets that don't exist (but are created by new technologies) simply cannot be analysed, and also that small markets don't solve the growth needs of large companies. He emphasizes the truism that technology supply may not equal market demand. Indeed, there are ironies and paradoxes to his notion of disruption, because often disruptive technologies are poorer performing and yield lower profits than current best practice.

The roots of theories of disruption can be traced long back, but in the past 80 years have been inspired by Joseph Schumpeter's writings on creative destruction and waves of change.[4] This thinking led directly to work on business cycles and their application to analyses of patenting trends and other measures of technological change. More recently this approach has been brought together with evolutionary and resource-based theories of the firm, which emphasise the

4. Determining what is and what is not destructive or disruptive (or "radical" or "breakthrough" or "really new") is a matter of constant debate, recently the subject of a study which attempts to measure the effects of innovation in terms of economic impact: Mario Coccia, "Measuring intensity of technological change: The seismic approach" *Technological Forecasting & Social Change* 72 (2005) 117-144, which also has a large bibliography of relevant references.

ways in which capabilities are acquired through regular and predictable behavioural patterns (or "routines") and how firms can be analysed as sets of capabilities, procedures and decision rules.[5]

Both these and other theories of technical change emerged from the perhaps disappointing observation that the best ideas, designs, and even marketed products don't always win through in the end. Entry paths of new products are distorted by the significant market power of incumbents, or regulators inhibit or even ban good new products from reaching markets. Often these two dynamic features are related and we see conflicts between competition policy and innovation policy.

Partly in response, but also as an instrument of leadership, we operate regulatory and other governance mechanisms that provide incentives, often in the form of stabilised investment climates, for technical change. For governance to have an effect, it needs to be realistic about the technical capabilities and resources it has access to, just as companies do when they shift functions around to stimulate or accommodate innovation. Too often those responsible for shepherding new technologies lose track of the relationships their capabilities and resources have to social and organizational norms, incentives and expectations. Organizations, as much as society in general, are affected by fashion, but often general behaviour that makes people receptive to innovation and novelty become engrained in national and regional attitudes.

Systematic studies have identified the main types of players in introducing new technologies and have characterised the various incentives of early adopters. Such innovators, in some places commonly called "champions" take on the role to organize resources and advocate particular changes. Some large companies set up adversarial or market-like systems to generate and stimulate such activities. Independent enthusiasts, even amateurs, are occasionally instrumental in promoting new technologies and the recent history of the Internet has been massively influenced by end-users and other tinkerers. Most big pushes, however, tend to emerge from strategies for market dominance. Those strategies often are informed by tools and techniques intended to help conceptualize technology futures. The most common ones include "roadmapping", a method that extends project management approaches and software tools, and "scenario building" which typically combines expert consensus building with probabilistic risk models or game theoretic techniques to project technical change trends and diffusion rates.[6]

5. There is a large and growing literature applying these concepts, perhaps best articulated by the writings of Richard Nelson and his collaborators and students in works such as R. Nelson and S. Winter, *An Evolutionary Theory of Economic Change* (Harvard 1982) and applied to technology studies in textbooks such as J. Howells, *The Management of Innovation and Technology* (Sage 2005).

6. One excellent example of this is to be found in the Stern Review on the Economics of Climate Change, http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/sternreview_index.cfm

Diffusion is also extraordinarily difficult to predict as it is highly sensitive to a wide range of forces. Indeed, that is why strategic planning for the introduction of new products is such a fraught commercial activity, with endless debates about the longevity of products, the slope of "S"-curves,[7] and how much of a loss is appropriate when introducing a risky new venture. The particular characteristics of certain kinds of high technology products and processes raise an additional dimension that is apparent where the ultimate user is separated from the producer by a skilled intermediary, as is the case with all prescription medicines, but also characterises infrastructure industries, office equipment, and other professional services like architecture. As difficult as the spread and uptake is to predict in such cases, it is here where regulation and other instruments of governance have the most effect and where policy planning is not only more effective but where its absence has at least as profound effect as active intervention.

Diffusion and improvements in technology almost always occur simultaneously, as does the growth in variation of applications. In practice, any measure that slows diffusion will also slow the rate at which related innovations occur. This is central to our understanding of the relationship between innovation and diffusion, which should not be seen as separate activities but which are related to the incentives associated with property rights regimes; there may be a trade-off between more secure property rights to encourage invention and less secure property rights to encourage diffusion. Since innovation implies the application of new possibilities in lieu of old practices, the context of users/consumers is crucial, as is the role of enterprises. Organisations that experiment are both more prone to introducing successful innovations, and more likely to be able to cope with the effects of rapid changes that affect them. Such organisations tend to deal well with risks and are flexible.

However, most things don't change, or change in very predictable ways, as we can see with the slow deterioration and consequent renewal of the housing stock, roadways, and the amortisation of other fixed assets and sunk costs. For more abstract concepts associated with the usage of technologies, we can use theories of path dependency and see how legacy systems and institutions provide the base upon which new structures are built while at the same time locking-in organisations at least in so far as investors have disincentives to write-off costs. This is one of the key drivers of business cycles and helps to explain why some economic situations are more or less amenable to large-scale changes. However, minor disruptions are common. New technologies replace

7. "S"-curves plot some indicator of take-up, often measured as a proportion of the target population, plotted against time. The long lead-up to the acceptance of a new product is indicated by the bottom left of the curve. The (often rapid) rise in the diffusion is charted by the middle of the curve and the approach to saturation is shown by the top right of the S-shape. Various policies and practices can accelerate or delay especially the point where the curve begins to rise, and what constitutes saturation might be measured by many different things; families with a certain level of disposable income, people living in urban areas of a certain age, geographical coverage, or the total population.

old all the time;[8] some moving in short cycles often spurred on by fashion [computer games, packaged food novelties], others go in longer cycles [major changes in the telecoms industry seem to occur on about 10-year cycles – although we seem to be late on the next one].

Major disruptions have been associated with technologies that have had wide applicability and address key aspects of the foundations of technical systems.[9] It is not always easy to see this as it is happening and the greatest challenge is to differentiate between dreams and those things that have such foundational effects early on. The steam engine, for example, was not revealed as a foundational technology until it became effectively applied on a large scale to trains, big factories and huge steamships. In the long years leading up to that, it attracted much attention and enthusiasm but was dismissed by many as of marginal interest.[10]

In order better to visualise the problem, let us consider a couple of 40-year periods in recent history and choose three major types of discontinuity that characterise each era. The first one I choose is the years around the turn of the last century, 1885-1925. We can begin to characterise the period in terms of:

1. Mass participation in public affairs, warfare, consumption; effects of the media.
2. Steamships/telegraph and associated capitalistic transportation and communication ventures that revolutionised investments and created, among other things, new relations with colonies and markets, and with capitalistic abstractions and instruments such as futures markets.
3. Utilities (especially water, sewage, gaslighting/electrification), and streetcars/light rail/underground/bus networks transformed cities and the lives of the kinds of people who lived in them. Horses left city streets (a cause of and symbol of a change in life, employment, civic environment, etc).

This era seems to us to be a unit – almost a tangible period when the modern world was being built. We associate it with the Boer War and the First World War, with the grand parliamentary debates and with the birth of a self-conscious identity of government as modernisers.

8. One graphic indicator of this is in the influential study by J. Langrish, M. Gibbons, W.G. Evans and F.R. Jevons, *Wealth from Knowledge* (Wiley 1972) in which they investigate 84 innovations that received the Queen's Award for technological innovation in 1966-1967. They found that only 11 were "fairly major changes".

9. However, the problems associated with projecting the effects of such major changes are described in Ph.W.F. van Notten, A.M. Sleegers and M.B.A. van Asselt, "The future shocks: On discontinuity and scenario development" *Technological Forecasting & Social Change* 72 (2005) 175-194.

10. When we look for those effects we should consider markets and organizations and the institutions that guide them. One clear indication of the transformative effect of the internet is the way in which peer-to-peer file transfers create new forms of value exchange. This can be contrasted with the model of Amazon.com, where the on-line shopping activity is largely a facilitator of retail commerce and not an alternative to purchasing. It of course has huge economic and social effects, as any independent bookseller can tell you, but it does so by competing with that bookseller, not replacing the concept of selling books.

The technologies associated with the discontinuities were largely introduced through slow changes in public policy and through large organisations such as the post office, trading and shipping firms. They were adopted by government and big business in leading sectors and in urban areas, and were disseminated through the provision of infrastructures of various forms.

The second forty year span I choose is the more recent period, 1945-1985, an era that now seems we can manage in one bite, even if it causes indigestion.[11] This is a period in which we can characterise three major discontinuities as follows:

1. Organisational principles were widely applied, with the help of social sciences including psychology and information and communication technologies and their associated managerial principles. Bureaucracies became highly efficient and professional techniques (including financial management) deeply integrated into most large organisations. The effects were felt throughout the United Kingdom and changed not only our expectations of government services but our attitudes as employees and consumers, bringing about wide-ranging social and market changes.
2. Mass higher education deepened the skills base in the United Kingdom such that fewer skills needed to be considered rare. This deepening of the capabilities available for all manner of professional and technical occupations and the increased flexibility of the workforce brought about major changes in the lives we lead, the work we do and our ability to maintain our competitive position internationally.
3. Changes in education and lifestyle as much as health care brought about the mass rise in longevity and of productive life. We changed our assumptions about normal states of health and, although healthcare costs continued to grow as a proportion of gross domestic product, cost-efficient technologies as much as new organisational practices associated with public funding were effectively used in this country to keep in check cost explosions such as that suffered in the United States.

These technologies were introduced mainly by private bodies, both large and small, and by government policies that largely dated from the immediate post-war years. They were adopted by the general public as citizens and consumers and disseminated by institutions of norms and by the building of infrastructure (including that of the NHS).

11. Of course I am skipping the interwar years and the changes brought about during the Second World War, but I do so mindful that most innovations of those years in any case had economic impact on U.K. civilian life only starting during this period, including nuclear power, rocketry, antibiotics, computing, new materials technologies, etc.

Now we turn our attention to the discontinuities that mark the coming forty-year period, from now to 2045. There is a trick in turning our attention to this period because although it is of the same length as the previously chosen two, it is naturally bewildering for us to think of the future in anything like the same way as we do the past. But that is exactly the point I wish to stress; when thinking of the next 40 years we should not be imagining a world of The *Jetsons* with most elements of our lives exactly as they currently are but wherein we play with either trivially "advanced" gadgets or alternately defy the laws of physics and biology in a science-fiction land free of energy costs, diseases and even gravity. There are many possible futures and it is folly to privilege any one vision over another. However, most of what we can imagine rests on things already in development. Indeed, we can find people making investments of money, time and prestige in all such ideas, and none, of course, in unanticipated areas of knowledge.

2005-2045

1. *Ubiquitous ICT:* As an extension of the existing trend, we can project further technologies and institutions accommodating the ubiquitousness and connectedness and "virtual" character of business and personal communication and computation capabilities. Even without imagining the end to the constraints of space and time, we can see that rapid and effective application of computing (the product of continued developments in processing speed through materials and nanotechnologies and associated software advanced and their accompanying decrease in real costs) will continue to allow for ever "smarter" and more energy efficient buildings, infrastructures, and coordination mechanisms. These will change our behaviours associated with proximity relations and some social and business conventions of temporality.

2. *Customisation:* As an application and product of the ubiquitous character of ICT, we are likely to see changes in our ability to simplify[12] and customise products and processes. These will be feasible through the utilisation of better man-machine interfaces (including virtual-reality techniques) and will be very widely applied using technologies associated with what we now call self-organising systems, ad-hoc, mesh and sensor networks, and applications of technologies such as peer-to-peer file sharing. They will be supplemented by identity tracking technologies including those that we currently see as early adopters of radio-frequency ID (RFID) devices and their control mechanisms. We can also imagine that along with advances in more effective energy production and storage techniques, customisation technologies will be applied to increase energy efficiency.

12. By simplify, I mean also hiding complexity, as when we place enhancements "under the bonnet" of the car.

3. *Biology:* We have become used to rapid changes in health care methods and we will continue to see the application of technologies to body control and we will devise strategies to deal with their cultural and environmental significances. These will include further changes in the ways we use chemical controls on the body and more psychological control mechanisms are likely. Some of these will provide tool-like bio-extensions, probably using embedded sensors or similar controls. Our impact on the wider environment may take the form of efforts to increase the humanization of the natural world through genetic manipulation and modification and other tools to affect bio-diversity. It will certainly affect agriculture and eating practices (whether or not the current approaches to genetically modified foods are maintained). This also suggests that we may face new challenges with regard to our identity and relations between the self and our environment. I doubt that this will affect our ideas of humanity, but it may change the way we think of other fundamental concepts, such as race.

All three of these chosen discontinuities hold the potential to undermine, or at least challenge, many assumptions about egalitarianism, human rights, and other democratic principles associated with privacy, identity, access, and choice. I will not deal with these features here other than to remind readers that no choice about technologies can be neutral and that political and legal mechanisms, especially as regards regulating use, are within our hands. These trends are not going to be unique to the United Kingdom, even if this country is likely to remain at or near the forefront of their development. As the recent activities with relation to stem-cell and human cloning research have shown, we can make funding decisions that accelerate or decelerate work along such lines domestically, but given the mobility of scientists and the behaviour of other nations, we have only marginal influence on the research front internationally.

3. General Purpose Technologies

When analysing technical change, it is helpful to make a conceptual distinction between what might be called discreet technological elements (single products or processes) and "general purpose technologies" [GPTs]. Technologies that underlie a wide range of activities, such as the computer-led information and communication technologies, can be regarded somewhat differently from others in that they are applied in diverse ways and the facility with which they are used greatly affects their impact on, among other things, productivity, qualities of life, and even cultural pursuits. Those that are the focus of much current debate include biotechnology (especially as regards genetic modification) and nanotechnology (especially as regards the production and use of new materials).

Indeed, one way of structuring the discussion of future critical technologies is to consider GPTs separately and ask questions about the significance of aggregate, large scale changes in the development of a GPT. This would lead us to look, for example, at the spending trends (by government as well as private bodies) in the basic science and engineering research in biotechnology and the relative penetration of early results from initial investments. Most of the major disjunctures described in the preceding section were based on what have been called "transformative" GPTs in that they led to massive changes in many, sometimes most, characteristics of economic, social and political structures. Other technologies are also general purpose, but, like lasers,[13] do not cause extensive structural change.

There have been very few major transformative GPTs (perhaps as few as 20 in modern history), and this should make us think very hard about judging those technologies that we are currently familiar with and assuming that they will have a truly transformative effect (no matter how profound we might otherwise judge them to be).[14] That is not to diminish the significance of any successful technology, and all technical systems require alterations to the structure of the economy, or at least of the ways in which a few of us conduct our business or

13. Richard G. Lipsey, K.I. Carlaw & C.T. Beker, *Economic Transformations; General purpose technologies and long term economic growth* (Oxford 2005) do not regard lasers as a transformative GPT because, although lasers "are used widely throughout the economy for multiple purposes: to measure interplanetary distances in astronomy; to read bar codes at retail checkout counters; and to facilitate numerous types of surgery in hospitals. They are instrumental in communications; they cut diamonds; they are used to mill materials in new cutting-edge machine tools; they weld plastics; and in the future, they may facilitate the usage of nano-technology. Lasers, do not, however, qualify as a transforming GPT because they fitted well into then-existing social, economic, and institutional structure, causing no major transformations." (p. 13).

14. We can regard GPTs as containing all of the derivative technologies treated as separate entities. This raises many questions about what Joel Mokyr calls "macro inventions", some of which are GPTs and others are clearly not, such as the bicycle and the screw propeller. See his book *The Lever of Riches: Technological creativity and economic progress* (Oxford 1990). His list includes: The three-field system, the heavy plough, the windmill, spectacles, the weight-driven mechanical clock, blast furnaces and the casting of iron, the printing press with moveable type, coke as a power source, the stocking fame, the steam engine, the breast wheel, the hot-air balloon, chlorine bleaching, gaslighting, the power loom, the bicycle, the Jacquard loom, chemical fertilizers and pesticides, the gas engine, screw propellers, the pneumatic tyre, Bessemer-type steel, aniline purple dye, the dynamo, pasteurization, indigo dye.

our social lives. Those alterations typically proceed incrementally and are easily absorbed into our institutions. Others cause extensive structural changes and affect “the organization of work, the management of firms, skill requirements, location and concentration of industry, and supporting infrastructure.” (Lipsey et al., p. 13)

Following Lipsey et al., we can define a GPT as “a generic product, or process, or organizational form that, although it evolves over time, is recognizable as one generic thing throughout.” (p. 94). They go on to point out that:

> *“GPTs are typically use-radical but not technology-radical. For example, the steam engines that powered the iron steamship had a long evolutionary history stretching back over more than two centuries before they had evolved enough to be used in large ships. The iron steamship was, however, a radical innovation in the transport industry and could not have evolved out of the sailing ship that it replaced....what distinguishes GPTs from other technologies is a matter of degree. So there will always be technologies that on our definition are almost, but not quite, GPTs. … Since GPTs are not born in their final form, they often start off as something we would never call a GPT and develop into something that transforms an entire economy…”* (pp. 96-97)

These transforming GPTs fall into six (sometimes overlapping) categories: materials technologies, power, information and communications technologies, tools, transportation, and organization and, as shown in the following table, can also be classified in terms of whether they are process technologies (PR), product-related (P) or organizational transforming technologies (O).

No.	GPT	Date	Classif.
1	Domestication of plants	9000-8000 BC	Pr
2	Domestication of animals	8500-7500 BC	Pr
3	Smelting iron	8000-7000 BC	Pr
4	Wheel	4000-3000 BC	P
5	Writing	3400-3200 BC	Pr
6	Bronze	2800 BC	P
7	Iron	1200 BC	P
8	Waterwheel	Early medieval period	P
9	Three-masted sailing ship	15th century	P
10	Printing	16th century	Pr
11	Steam engine	Late 18th to early 19th century	P
12	Factory system	Late 18th to early 19th century	O
13	Railway	Mid 19th century	P
14	Iron steamship	Mid 19th century	P
15	Internal combustion engine	Late 19th century	P
16	Electricity	Late 19th century	P
17	Motor vehicle	20th century	P
18	Airplane	20th century	P
19	Mass production, continuous process, factory	20th century	O
20	Computer	20th century	P
21	Lean production	20th century	O
22	Internet	20th century	P
23	Biotechnology	20th century	Pr
24	Nanotechnology	Sometime in the 21st century	Pr

4. GPTs, networks and infrastructure

A key feature of general purpose technologies is that they exhibit certain of the features of infrastructures, and some features of networks. This makes some aspects of their trajectory somewhat more predictable than other developing technologies. Let us consider some of the key features of networks first. One of the central concerns of policy makers in network industries is the prevention of abuse of dominant positions by firms. That abuse, economists fear, can create inefficiencies and welfare loss. One aspect of that at least is the possibility that abusing firms forestall technological development. On the one hand this makes it somewhat easier to predict those technological trajectories; after all, the telephone network technology based on landline phones connected by copper wire through electromechanical switches persisted for many decades, leaving technology forecasting activities with little to do so long as national operators such as BT held dominant positions. Another feature is that in networks relatively small differences in effectiveness (and not necessarily technological efficiency) can be translated into large differences in market share.

Can government's position as regulator in infrastructure industries be analogous to its role in R&D? The overriding purpose of government regulation, it is supposed by regulators, is to avoid or correct for market failure. In terms of technological trajectories, market failure could mean the persistence of an undesirable technology at the expense of the development of another. However, we have to be careful with this concept because just as we would wish to avoid (or at least diminish) the dominance of an old technology firm where a new industry could arise, we also would not wish to introduce distortions into markets or other systems that boost inappropriate technologies. Furthermore, these choices are context-bound. Nuclear energy, once heralded as a future GPT and favoured by regulation and subsidy in this country, failed to take off here for apparently good reasons; but it is a very different story across the Channel where the French government did more to ensure that it became the dominant source of energy.

Restrictions on certain kinds of entry, especially in network industries, have been effective in changing the trajectory of technology in some cases. For example, the US government restricted AT&T from moving out of telecommunications and prompted the company to license some very influential technologies, such as UNIX. The restrictions placed on BT were probably a significant factor in the rapid uptake of mobile telephones in the UK, and also of some accompanying innovations (an example of which might be the various uses of SMS).

Markets seem inadequate always to choose reliably the most efficient standards and governments have often seen the desirability of entering standards disputes to resolve uncertainty or pre-empt decisions. An example of this was the GSM standard agreed in Europe and its subsequent effect in the US. But the ultimate impact of this difference is difficult to resolve. On the one hand, GSM stimulated markets and smoothed dissemination, a supply factor that affected the diffusion process, shifting the rate and direction of technical change. Conflicting and competing standards in the US stimulated some valuable innovation that may yet prove to provide a better entry position for more advanced mobile services. This dispute between US and EU standards may look arcane and marginal in comparison to the effects the industry has had in Japan and Korea.

Lock-in effects have been much discussed but are still not well enough understood. The most common examples are QWERTY, and Betamax vs. VHS video standards where the generally discussed story is one of an inferior standard quickly capturing the market and blocking out superior alternatives.[15] But in many of these cases the quality features are not well enough established to resolve the cases, and their network effects on a larger scale are not convincing. Furthermore, apparently excellent standards, such as wireless application protocol for mobile telephony (WAP) failed to stimulate markets sufficiently despite considerable investment.

One recent government report claimed, as stated in the section on "Greater responsiveness of the research base to the economy" 1.19, that "currently the UK's industrial R&D base is fragile and heavily dependent on the investment decisions of a dozen large companies, concentrated particularly in two sectors: pharmaceuticals and defence."[16] However, the associated "Science & innovation investment framework 2004-2014" identifies six areas of exemplary multidisciplinary research themes that are "likely to be of international importance over the next ten years...in which the UK has current world-class strengths and could develop a lead…"(p. 28ff, section 2.30): sustainable Earth systems; systems biology; sustainable energy; cognitive systems; cyber trust and crime prevention; identities and cultures. It would be worthwhile reflecting on the extent to which these are related to GPTs, are likely to become GPTs themselves, or fall outside the scope.

15. It remains unclear whether QWERTY is indeed inferior, and what set VHS firmly ahead was when it became clear that more products would be generally available in that format.

16. (HM Treasury, DTI, Dept. for Education and Skills, "Science and innovation: working towards a ten-year investment framework" HMSO, 2004; section 4.3, p. 25 www.hm-treasury.gov.uk/media/D13/9D/science_406.pdf; accessed 21 November 2005)

5. Rates of technological innovation and diffusion

In general the best predictor of a population's adaptation of new technology is economic wealth.[17] Other factors that can be correlated are measures of human capital by which we include especially education and the ways in which it is deployed. The institutional legal environment has been shown in many studies of, for example, the diffusion of the Internet, to be crucial. These factors have long been taken into consideration in relation to investigations of the effects of markets; that somehow innovations are '"called forth" or "triggered" in response to demands for the satisfaction of certain classes of "needs"'.[18]

We must also take account of possibly politically disquieting effects of new technologies, including those that cause social unrest or large-scale burning of assets. These are also both context specific. For example, mass demonstrations against genetically modified foods might forestall the spread of such products, and we have had a foretaste of that in Britain, but not so much elsewhere. Who protests also makes a difference. Where the general public protests it may indicate that the market for some consumer product could collapse. Where farmers protest it may be that they are engaging in one or another form of luddite response. Public reactions for and against new technologies do affect rates of innovation and diffusion, but then so do many other factors. Let us consider the diffusion rates of some exemplary technologies.

Electrification in the UK

Electrification is one of the key transformative GPTs of the past century and its diffusion is one good indicator of how such technologies spread. However, it is not a straightforward story because of the different rates of growth of different usages of the technology. Electrification for lighting started before the 1890s and rose exponentially to about 1903, the rate of growth flattened for around seven years, and began to rise again around 1910. The use of electricity for general power started only around 1900 and rose exponentially to (and I believe through) the First World War. Traction, however, was a major use that started in 1899 (application to streetcars began before electricity became widely available for general use) and the rate of growth rose rapidly to about 1904, after which it flattened out.[19] Rates of invention and innovation in electrical appliances,

17. E.M. Rogers *Diffusion of Innovation* 1995 (4th ed. New York: Free Press) is the best known such study, but there have been many others that support this view.

18. David Mowery and Nathan Rosenberg, "The influence of market demand upon innovation: a critical review of some recent empirical studies" in N. Rosenberg, *Inside the Black Box: Technology and Economics* (Cambridge 1982) p. 194. They go on to point out that "What is needed is to sort out the issues and improve the formulation of policy is a stronger predictive theory of innovation, one that goes beyond simply considering the motivations of individual firms to undertake research projects, and that deals instead with the mechanisms by which this motivation may be transmuted into an innovative response of a particular sort, one influenced heavily by such factors as the supply of applicable science and technology....Rather than simply referring to "lags" in the process, a useful theory of innovation must try to explain the varied length and distribution of such delays in the response to "needs". (P. 195)

19. Leslie Hannah, *Electricity Before Nationalisation* (Macmillan 1979, p. 17) and R. Byatt, "The British Electrical Industry 1875-1914" unpublished DPhil Thesis, Oxford U.

generating and distributing equipment, and all manner of related uses remained robust from the late 19th century through the 20th century, and if we include electronics then we can see a continuous rate of growth of innovation.

Telephones and the World Wide Web[20]

Telephone technology took five decades to reach 10% of the households in the United States and its diffusion in the UK was considerably slower (but faster in some places, such as the city of Stockholm, in Sweden, where the industry structure and its economics was different). The World Wide Web took five years to reach 10% of households, but that was based on the existence of the internet in its previous form as a network used by academics and governments. Chen and Crowston summarise the contrast in this way:

> *To those living in the late nineteenth century, a device to transmit an actual humans voice was a completely new concept. People were scared, puzzled, and awed. Because it was invented in a relatively conservative social system, such an innovative technology took a longer time to spread out. In contrast, Web technology is compatible with its embedded environments, builds upon the existing Internet structure, and consequently can diffuse very quickly.*

The telephone required every user to be educated into a new form of communication and new uses for it had to be found. In contrast, Web technology moved very quickly upon the base of a very well educated mass of early adopters and a concerted effort on the part of the inventors and early users to create a snowball effect. The early stages had few implications for sunk costs, as computing equipment could generally accommodate what was needed to participate. The first Web server was introduced in 1991 but by the beginning of 1993 there were scarcely 50 web sites in the world. By October of that year there were over 600 servers and by the next June there were 2,700, by June 1996 there were 230,000 Web servers and the number almost tripled over the next eight months with approximately 45 million people using the Internet, most of whom were by then Web users. Innovation in the Web, stimulated especially by massive levels of inventive activity by users, continues to be extremely active, and although exponential rates of growth in innovation will not continue, the level of activity remains very high.

Both the Web and overall telephone use have been dependent on transatlantic telephone cables, the first modern one of which began to operate in 1956, a century after the first telegraph line was connected. Per minute usage costs remained high until the 1970s and dropped further from 1988 when the first fibre optic transatlantic cable was deployed. The number of voice circuits then rose steadily until the late 1990s when companies such as MCI engaged in massive building based on investments presumably associated with rapid growth in data

20. H. Chen and K. Crowston, “Comparative diffusion of the telephone and the World Wide Web: An analysis of rates of adoption” (1997) http://crowston.syr.edu/papers/webnet97.html

traffic, primarily using Internet Protocol.[21] This, of course, was one of the contributing features to the dramatic collapse in telecommunications industry share values in the United States and elsewhere.

Commercial aircraft[22]

The early history of the aircraft is well known, but perhaps what is less well appreciated is the role of the U.S. Post Office in stimulating the diffusion of the technology by transferring airmail transport to private contractors in 1925. Bids were opened to private contractors on a paid by weight basis and as airmail postal rates were reduced, volume grew rapidly. The resulting contractor profits made it feasible for aircraft producers to design larger aircraft which were further enlarged when incentives were offered through changes in charges to mix in a larger number of passengers with airmail. By the mid 1930s concerns about passenger safety and regulatory policy led to the adoption of new aircraft designs by the major carriers, which Mowery and Rosenberg explain was:

> *based on their belief that rapid introduction of state-of-the-art aircraft was an effective marketing strategy when price competition was not possible. The drive to be first with a new design strongly motivated major airlines to make early purchase commitments to airframe manufacturers as a means of achieving the earliest possible delivery. Service quality competition fostered rapid diffusion and adoption of innovations drawing upon government-supported research, and supported fierce competition among manufacturers.*

The story of this industry is seen as an example of how important it can be to affect both supply and demand for innovation and technical knowledge.

Railways

When we consider railways, we can see the rapid emergence of "S"-curves when charting the rate at which they are being built. We see, for example, that the lengths of the seven longest rail networks reached the top of the "S" in Britain already by the pre-First World War period (the curve begins to slow already by around 1880), whereas in Germany the rate of growth continues up to the outbreak of war in 1914, and the shape of the curve for France is similar, although France's network never reached the density of Britain, and by the interwar years Germany had built a denser network than the United Kingdom. The curves describing India and Russia (and then the USSR) continue to grow until the late 1920s.[23] The factors in the growth of these networks has a great deal to do with investment practices, transport industry structure, and topography. Similar technologies were available to all railway network builders with most

21. An interesting discussion of this can be found in Ilkka Toumi, *Networks of Innovation, change and meaning in the age of the Internet* (Oxford 2002)

22. Largely based on David C. Mowery and Nathan Rosenberg, "Technical change in the commercial aircraft industry, 1925-1975" *Technological Forecasting and Social Change* 20 (1981) 347-358

23. These comparisons of the rate of growth of key technologies are fascinatingly analysed in Daniel R. Headrick, *The Tentacles of Progress; Technology Transfer in the Age of Imperialism*, 1850-1940 (Oxford 1988), pages 55ff.

patents taken out by British, German and US-based inventors and resulting products were made widely available. So we do not see many engineering differences among countries, but systems differences abound.

A general comment on rates of technical change

All technologies are, at some level, parts of systems that encompass other technologies, bodies of knowledge and practice, and communities of people who have intellectual, economic and political agendas. The cases highlighted above all point out the manner in which it is the coordination of these elements that determines the rate and direction of innovative activities. One analogy, popularised by Thomas P. Hughes,[24] is of the front line of an advancing army that quickly gets distorted by pockets of resistance, topography, mechanical or organizational problems, etc. These distortions create "reverse salients" that must be overcome before resuming the advance. Some such reverse salients, such as persistent problems with energy consumption in third generation mobile telephones, can be identified by outsiders by noting how interested parties deploy resources disproportionately to solve them. This might be evidenced by large amounts of research and development funding flowing to a hither-to unanticipated problem area, or the proliferation of patenting activity in a certain field, etc.

One indication of this emerged from a study by Gibbons and Gummett of key research events involved in each of five innovations: magnetic ferrites, the video tape recorder, oral contraceptives, the electron microscope, and matrix isolation.[25] They traced the underlying science and technology for these innovations and found that the vast majority came from "nonmission-oriented" work much of which was completed at least 30 years in advance of the innovation (45%) and for fully 80% it was completed 15 years before the innovation.

Future innovation rates

Will the rates of innovation go up or down over the next 10 years compared with the last 10 years? Futurists have argued in both directions, for example, Ray Kurzweil argues that the rate of innovation is increasing, while Paul Saffo is less bullish.

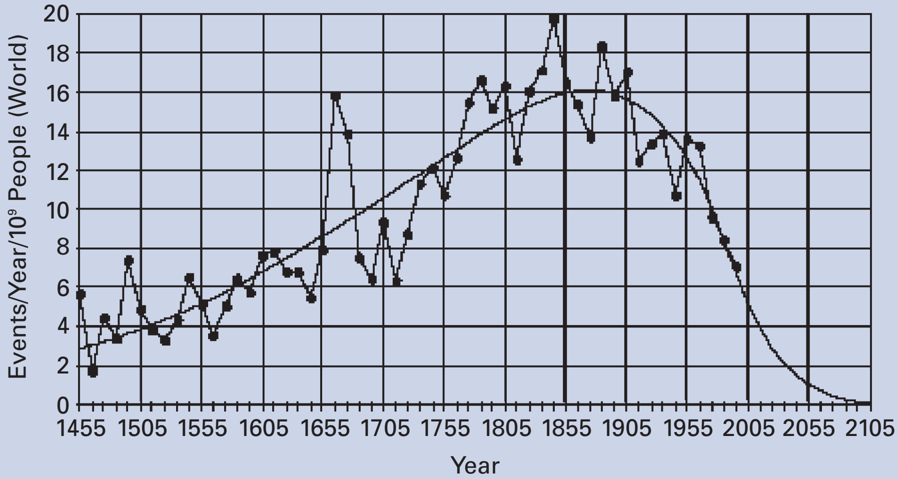
Most indicators of growth (population, wealth and disposable income, number of firms, numbers of scientists and technologists employed, educated consumers, etc.) would argue for continued rising rates of innovation. We have a more substantial argument if we ask whether controlling for these factors the rate of increase in innovation will continue over the next 10 years, and whether the contribution of the UK to that *rate of increase* will be as significant as in the recent past.

24. See T. P. Hughes, *Networks of Power: Electrical Supply systems in the United States*, England, and Germany (Johns Hopkins 1983) and his "The evolution of large technological systems" *The Social Construction of Technological Systems*, ed. Wiebe E. Bijker, Thomas P. Hughes, and Trevor J. Pinch (MIT 1987)

25. M. Gibbons, and P.J. Gummett conducted this research in the mid 1970s and it is reported in a variety of places, including M. Gibbons, "Is science industrially relevant? The interaction between science and technology" in M. Gibbons and P. Gummett (eds.) *Science, Technology and Society Today* (Manchester 1984)

An argument against rising rates of innovation

Figure 1: Rate of innovation since the end of the Dark Ages



Source: J. Huebner/Technological Forecasting & Social Change 72 (2005) 990-986

Note: Points are an average over 10 years with the last point covering the period from 1990 to 1999. The smooth curve is a least squares fit of a modified Gaussian distribution to the data.[26]

A few factors can be pointed to that make us inclined to feel that innovation will not continue to be healthy. One is that it becomes increasingly more expensive to produce innovations of significance and sources of funding are not increasing commensurately. Indeed, insofar as significant sources are being made available from private sources, they are disproportionately being channelled away from UK institutions. An example of this is the current practice of BP to channel about 80% of their R&D funding to institutions in the United States, the remaining 20% being distributed to the whole rest of the world, including the UK.[27] Another indicator of this is the recent drop in the amount of industrial funding of R&D in UK universities by industry.[28] One further argument occasionally arises to cast doubt on the sustainability of familiar rates of increase in innovation takes a form of the statement that “everything important has already been invented”. This seemingly absurd claim has had some currency in the telecommunications industry where there has been a feeling, commonly expressed by both the investment community and corporate strategists, that during this recent period of poor resources, falling incomes, and tough competition, innovation is only making things worse by shortening the lifecycles of commercial products (such

26. Jonathan Huebner, “A possible declining trend for worldwide innovation” *Technological Forecasting and Social Change* 72 (2005) 980-986. Huebner’s work suffers from much the same kind of problem that many calculations of “major innovations” do in that it is dependent on an idiosyncratic listing of important events plus the highly incomparable indicators of various patent data analyses. Huebner does remind us that world population is probably rising faster than the rate of patentable inventions, but it not very convincing that innovation peaked in 1873 and will become negligible in 2023. See also two “Discussion of Huebner Article” pieces by Theodore Modis and John Smart, and Huebner’s response, in the same volume (pp. 987-988, 988-995, and 995-1000).

27. BP claims that this practice is reinforced by the fact that almost all the truly pinnacle research institutions are located in the US, notwithstanding efforts to promote so-called “centres of excellence” in British universities. BP makes it clear that their funding of UK university research must be regarded as supplementary to rather than instead of other forms of university income.

28. *Times Higher Education Supplement* 1 December 2005

as mobile telephones) and services (such as low and medium speed broadband). It is further aggravated by the expectations of regulators and customers that any new service be rapidly disseminated and altogether it all becomes too heavy a burden. This is not generally used as an explanation for the decrease in R&D investment, but it is presented as an excuse to delay bringing expenditure back up to levels enjoyed up to around 2001.

Why the rate of innovation is likely to continue to increase

The pharmaceutical industry is now an industry with one of the most rapidly increasing rates of innovation and became so through a transformation that took place around one hundred years ago. Since that time all high technology/science-based industries have become dependent on rapid rates of innovation because that is a feature of their competitive environments. Although rates of innovation fluctuate in all such industries for idiosyncratic reasons (sometimes related to business cycles, sometimes related to trends in science and technology, and often related to national R&D policies), it seems unlikely that the coming ten years will see such a radical transformation of competitive and cyclical forces as to cause a radical slowing down in the rising rate of innovation. UK industry continues to take out a large proportion of patents filed internationally, new businesses are increasingly being founded in areas that rely on new technologies, and other indicators of rising innovative activity (and of pay-offs from investments in high technology) are likely to continue over the coming ten years. Furthermore, worldwide there continues to be rising rates of production of technically-capable graduates (even if the UK does not maintain rising rates of engineering students), and they are increasingly attracted to all the world's concentrations of employment of such people, including the southeast of England.

It is for these reasons, rather than for any particular expectation from nanotechnology or energy systems research or any of the other emerging technology, that I believe that rates of innovation will continue to rise, if modestly, over the coming ten years.

6. Prioritisation and policy implications for 2007-2017

Prioritisation cannot be a process of simply deciding which of the current trends are preferable and then choosing mechanisms to enhance or support their growth. To begin with, the information we have about trends gets distorted as soon as policies begin to intervene and the basis on which priority areas were chosen disappears as markets or other exchange regimes are affected. For that reason we need to find the means to obtain information about the relative value of the technology as it evolves. This is one of the most significant problems for long-term planning with large projects.

- Accepting that new technological knowledge, whether acquired from abroad or produced by domestic R&D, has major positive externalities provides a reason to encourage technological advance with public funds.
- Accepting that technology changes endogenously provides a reason why present comparative advantage need not be accepted as immutable; it can be changed by public policy as well as by the activities of private agents.
- Accepting that technological change is highly dependent on local contexts implies that the best policies are context-specific rather than being the same for all countries at all times.
- Accepting the conclusion that there is no unique optimum allocation of resources…has important consequences for how we view economic policy in the area of growth and technological change…Policy with respect to these matters must be based on a mixture of theory, measurement and subjective judgement (from Lipsey 2005: 514-515)

These principles further imply that we should differentiate technologies of apparent worldwide importance no matter what happens in this country from foreign-sourced technologies that will have a specific impact upon the United Kingdom. We should also always keep in mind the impact in relation to the scale and scope of their effects, differentiating between those which affect one or a few companies from those affecting whole industries and infrastructures. Early on the impact of ICT on productivity was only seen in the ICT industry. It was obviously good for them, but the country has experienced a lag time between the period when major investments were made in ICTs to the period when productivity improvements could be unambiguously attributed to their effects.

When considering the next ten year period that describes the early, partial phases of the introduction, adoption and dissemination of the coming 40-year block of time, we can ask a few systematic questions of technologies being scrutinised.

- Which technologies are likely to be well-advanced and disseminated by 2017?
- Which do we suppose will be at an early stage?
- Which will still be “blue sky” or in infant stages?

What can we say about the curves that might describe the processes between the period 2007-2017? We can imagine curves that describe the initial take-up and diffusion of each technology. We can differentiate between transformative and other GPTs, and we can imagine national differences in the time period and shapes of J-curves that describe relative losses in the early stages of dissemination.[29] We could have some effect on the timing of British J-curves, and make a determination that Britain accelerates the onset of a J-curve such that the learning process begins earlier than might otherwise have done so.

From what we have already seen, we can describe a large number of criteria that can reasonably be regarded as significant when going through a prioritising process. However, a simple framework is useful and it is helpful to take three complex criteria and plot them on three axes, forming a space in which technologies can be judged in terms of their likely:

- scale and scope: by which we would take into account the pervasiveness of their utilisation and the extent to which they are dependent on vertical linkages
- temporal characteristics: by which we would take into account the likely rate at which they would be adopted and disseminated
- controls available: the policy levers available to us, including the government as sponsor of R&D and as procurer of future products (as typically takes place for armaments), the dispensation of research funding (to universities and other bodies), standards setting and regulatory activities, and other incentives such as those available through direct and indirect taxation.

29. Introducing new technologies typically involves both risk-taking and considerable initial investment. Indeed, these initial costs are extremely difficult to calculate even in retrospect because they would need to account for opportunity costs and many indirect costs as well as some difficult to measure direct costs such as those incurred through training, awareness-building, and transaction costs associated with governance, including regulation, enforcement, monitoring, etc.

7. Conclusion: how can we better engage in technology prioritisation?

A wide range of factors affect the introduction of new technologies, ranging from creative and inventive forces to market-pull, but we can use resources and levers of governance to affect the rate and direction, and especially the spread, of particular technological systems. We can also leverage the existing resources nationally, those areas of exceptional capabilities that can bring about disproportionate advantages. We can encourage and nurture early adopters, and create climates that foster investment and appropriate risk-taking. And we can help to create an atmosphere through incentives and regulatory controls that makes it attractive for emerging technologies to be exploited on a large scale here, as opposed to enjoying more nurturing environments abroad.

Prioritising will always be a process of bringing together a careful analysis of capabilities with an awareness of what is desirable. Only after that does it make sense to take into account the likely rates of diffusion and other temporal features of the early stages in the lifecycle of a technology. In this report I have stressed the differences between technological artefacts and general purpose technologies. I have also emphasised that not all general purpose technologies are transformative. By casting recent periods of transformation into 40-year eras, I have shown that very large scale changes do occur, but that major sources of technological change take a considerable amount of time to be noticed for what they are and before they have the massive impact we might wish on the economy and on institutions of society. Any ten-year planning period is one in which existing trends can be fostered, the seeds of future developments planted, and dreams encouraged. The fact that it is easier to prioritise existing trends should not distract us from thinking about what we should be doing in this first decade of the next 40-year period.

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Printed in the UK on recycled paper with a minimum HMSO score of 75
First published March 2007. Department of Trade and Industry. www.dti.gov.uk