Institute for Manufacturing

# Centre for Technology Management

***Complex Dynamic Processes in the Evolution of Early Information and Communication Technologies***

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No: 2005/02, November 2005

UNIVERSITY OF CAMBRIDGE

# Centre for Technology Management Working Paper Series



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I.S.B.N. 1-902546-44-X

**ABSTRACT**

The creation of novelty and its subsequent retention or elimination by evolutionary mechanisms is a central theme in complexity studies. By examining the evolution of three information and communication technologies, this paper explores linkages between variety generation, selection and propagation. Tensions are identified between the benefits of variety to meet diverse user needs and the value of standardization to facilitate exchange. In ICT industries, the usefulness of a product or service increases with numbers of users. The benefits of interoperability, the facilitation of complementary technologies around a standard and user switching costs are among network externalities. These contribute to the emergence of dominant designs and standard protocols, which reduce the variety of enabling or platform technologies but increase complementary product and process innovations. The linkages between evolutionary selection and propagation in ICT have accelerated the pace of innovation, but could in principle have the reverse effect, unless the effects of asymmetries of market power and proprietary standards are offset. Long term support for science and technology and entrepreneurial activity provide exogenous sources of variety that can renew innovation.

## I Introduction

The creation of novel forms and the effects of their subsequent selection or elimination is a central theme in complexity studies. Complex processes are at work whenever their outcomes impact on further activity in iterations that generate recurrent feedback processes. In Darwinian theory, sources of variation are independent of the selection which occurs through the elimination of non-adaptive variants. But in the evolution of technologies there are close linkages between the selection and generation of variants and their propagation, instead of each mechanism operating independently as in natural selection. While in natural systems the generation of variety is random and blind, in social systems, variety is often guided by desired outcomes since the experience of selection can contribute to learning. Uncertainty as to actual outcomes encourages a variety of responses, which together generate diversity of economic activity and outcome.

Evolutionary processes are not simply a biological metaphor when applied outside the natural world, but a distinctive mode of transformation in areas that include the evolution of languages, the development scientific knowledge and the advance of technologies. Evolution operate in a distinctive way in different arenas but there are common processes at work. Natural variety is generated through random genetic mutation and combination, blind to selection forces. But in the economy, intelligent agents can anticipate the rewards and sanctions exerted by selection forces, and so experience incentives to respond to them.[1] Consumer demand, the allocation of investment and competition have operated as selection forces shaping the advance of information technologies in recent years.

It is increasingly recognized that co-evolution operates as a meta-evolutionary process in which the interaction of participants contributes to the collective creation of a habitat that shapes their prospects (Goodwin, 1994). Co-evolution is the collective outcome of responses (whether or not intentional) and feedback effects that accommodate other participants in the system. Selected forms of mutual accommodation or symbiosis, can occur without intentionality when blind accommodating responses are rewarded by survival, or can be pursued purposively by human agents. In other words new variants may be engendered in anticipation of selection conditions, or without prior regard to their likely reception which occurs *post hoc* through natural selection,

[1] " … while no treatment of innovation can ignore a stochastic element, it is also true that innovation represents guided and intentional variation purposely undertaken in the pursuit of competitive advantage. Economic agents learn from experience and anticipate future states of the selective environment in a way quite unknown in biological or ecological selection." (Metcalfe, 1998)

though in a setting where fitness is related to capacity to fit into a co-evolving eco-system. When new variants are crafted in anticipation of the selective response, this accelerates the evolution of human artifacts if the selection regime favours innovation but may not do so when selection conditions are less conducive to change.

The focus of this chapter is on the linkages between evolutionary mechanisms in the emergence of new technologies. They are explored through examples in semiconductors, personal computers and electronic messaging. In these sectors, new ventures have been the agents of major innovations, raising questions about the way variety is engendered. Among other radical innovations produced by entrepreneurial entrants are the telephone, electric light, radio broadcasting, photocopying and bio-synthesised insulin (see e.g. Nairn, 2000, McKelvey, 1996), suggesting that this is a feature of the way technology advances. We pursue three further questions about evolutionary mechanisms in connection with ICT innovations.

1. What were the origins of the knowledge exploited by entrepreneurial ventures to produce innovations?
2. What were the mechanisms connecting *variety generation* and *selection processes* in the evolution of these technologies?
3. What were the mechanisms connecting *selection processes* and the *propagation* of these technologies? Did this involve further variety creation?

A complexity approach is used here to explore how small beginnings led to world-changing developments. The outcomes of evolutionary feedback processes cannot be forecast in any detail in natural or social systems subject to interactive feedback effects. But a complexity perspective can identify common dynamic processes that are not evident from the historical record alone, nor from cross sectional analysis. This study reveals a persistent dynamic operating between the diversity of user needs – met by multiple technical solutions – and the uniformities that make interchange possible. This emerges as a central feature of co-evolution. The study finds that this dynamic has until now accelerated technological evolution in ICT and identifies reasons why rapid innovation may not continue indefinitely without countervailing policies.

## II Industries and Innovations

Co-evolution occurs within an environment made up of producers and users. The conventional definition of industries is in terms of competing producers of classes of products (Barney, 1997). When the focus is the characteristic structure of an industry, the unaddressed issues are how industries emerge and are transformed over time. It has been proposed that a new industry consists of competing producer webs or networks: "a broad group of firms struggling to shape or influence the perceived value, nature, and technique for carrying out a particular activity" (Munir and Phillips, 2002 p.294). According to this perspective, it is not until an emerging technology matures that industries take on their characteristic structure after an early period of producer network activity. But from a complexity perspective, network activity is not confined to producers but extends to user or consumer groups and related organizations including professional organisations and standards bodies. These networks make up ecosystems of related production and consumption (Moore, 1996). Nor are production webs just a transitional feature of emerging industries; production networks persist and evolve in interaction with user groups and other participants in a business ecosystem.

In the next section we review the early emergence of the information technology and communications sector. We attempt to trace feedback connections between variety generation, selection and propagation. We go on to examine the swarming of innovations that occurred as the density of complementary technologies increased, and view the boom and slump as a further manifestation of complexity.

### 2.1. Semiconductors: the Integrated Circuit and Central Processing Unit

It was in the R&D laboratory of a successful early entrant to the electricity industry, Bell Laboratories, that the transistor was created in 1947. Constructed from semiconductor materials such as germanium and silicon, the transistor allowed the magnification of electronic impulses. It required less current, generated less heat, and was over fifty times smaller than the vacuum tubes earlier used for this purpose (Wolfe, 1983). With US government grants that continued into the Cold War, Bell Labs was funded in some respects like a public sector research institute. Within about five years, transistors were reliable enough for commercial use. They were exploited not by established companies, but by a maverick employee of Bell Labs, William Shockley, one of the co-inventors of the transistor. Returning to his home town Palo Alto, he set up a company, Shockley Semiconductors in 1955, to pursue opportunities opened up by the transistor.

This was the origin of a swarm of entrepreneurial endeavours that created the semiconductor sector in Silicon Valley, largely through multi-generational spin-outs. Shockley fell out with his employees, who left and started up their own firms. The first spin-out was Fairchild Semiconductors, originally a joint venture, and the first company to work exclusively in silicon. It was at Fairchild Semiconductors that, in 1959, Robert Noyce invented the integrated circuit, which combined a number of transistors, diodes, resistors and capacitors onto a single piece of semiconductor. Ten years later, Noyce had spun out his own company, Intel, with Gordon Moore. Within two years Noyce and Moore had developed the 1103 memory chip, the size of two letters in a line of type, each chip containing four thousand transistors. “At the end of Intel's first year in business, which had been devoted almost exclusively to research, sales totalled less than three thousand dollars and the work force numbered forty-two. In 1972, thanks largely to the 1103 chip, sales were $23.4 million and the work force numbered 1,002. In the next year sales almost tripled, to $66 million, and the work force increased two and a half times, to 2,528” (Wolfe, 1983). Other semiconductor ventures were drawn by these high returns, the numbers fuelled by large numbers of engineers produced by universities in the US and by employee departures to found new spin outs. By 1972 there were 330 semiconductor manufacturing firms in the United States (Freeman, 1995 p.234).

At Intel, Noyce aimed to hire the best people. One of these was Ted Hoff, who had spent over ten years in research at Stanford University when he was invited to join Intel. He designed a microprocessor[2] at Intel in response to a request from Japanese manufacturer for specially designed chips for their desk-top calculators.[3] He packed all the central processing unit (CPU) functions of a minicomputer onto a single chip. At first the Intel marketing team were not convinced of the prospects for the microprocessor because the processing power was viewed as insufficient. But the improved Intel 8080 that came out in 1973 was twenty times faster than the first 4004 chip. Intel’s core business was in computer memory, a sector which it dominated despite the numerous firms entering the sector (Grove, 1996). It did not at first recognise the

[2] A microprocessor is an integrated circuit designed to carry out most of the processing and control functions of a computer.

[3] Texas Instruments, where the integrated circuit had independently been invented, become Intel’s first competitor in the microprocessor market, coming out with their own chip to meet the specifications of one of Intel’s customers.

importance of the microprocessor, but the miniature size and increasing power of Intel's new products provided the core technology for the microcomputer industry.

## 2.2. The Microcomputer

Digital computers were developed in the 1940s, heavily funded by defence spending at IBM and elsewhere. During the 1960s and 1970s computing facilities became progressively more accessible with the introduction of timeshare systems and minicomputers. However, computers remained complex and expensive until the mid 1970s when the invention of the microprocessor made possible the development of the microcomputer.

The early days of the microcomputer provided new scope for entrepreneurs. The first ideas came largely from amateurs keen to gain access to digital computing. Entrepreneurial ventures experimented to create a variety of kits for these hobbyists, connecting up electronic components to the increasingly powerful chips available from young semiconductor companies. The first commercial microcomputer, the Altair, launched by a small business, MITS, in Albuquerque in 1975 had as its core Intel's 8-bit 8080 microprocessor. Hobbyist user groups supplied ideas for applications, such as games, music, databases and personal accounting. Small third party suppliers sprung up to provide software and add-ons. A compiler for the BASIC computer language was provided by young drop-outs from Harvard, Bill Gates and Paul Allen. Demand for the Altair outstripped supply and imitations were soon available based on the S-100 bus architecture and CP/M operating system of the Altair. New ventures, drawn to the emerging market, were experimenting with alternative designs and by 1977 a number of improved products were available, including the Commodore PET, Tandy TRS-80 and Apple II, each using their own operating systems and a variety of chips (e.g. the Motorola 6800; Zilog Z80). The Apple II, conceived as a consumer product by the young Steve Jobs, attracted customers well beyond the hobbyist market and sales increased from $750k in 1977, to $983m in 1983. At this early stage, the design of microcomputers included most of the now familiar elements: a microprocessor unit, a keyboard, a storage device and a monitor.

Users fuelled demand for microcomputers. In established computer companies, engineers were ordering their own microcomputers to by-pass interaction with the mainframe computers which then dominated the business market. As the ‘toy computers’ improved their performance, they made inroads into the markets of both mainframe computers and the more recent generation of mini-computers, produced by companies like Digital Equipment Corporation and Wang.[4] Mini-computers were more accessible than mainframes but still costly and beyond the reach of ordinary consumers and small businesses.

The emerging market also attracted the attention of what was then the world’s largest computer manufacturer, IBM. The first IBM Personal Computer (PC), launched in 1981, was innovative in introducing the first 16-bit microprocessor used in a microcomputer, the Intel 8088 chip. IBM’s entry into the microcomputer market attracted buyers in the business sector, faithful to its brand. IBM calculated that an open standard would encourage the production of software and IBM-compatible complementary products, enhancing their product. Users and suppliers were ready for a new standard that would allow for variation around a common format. The advent of the IBM PC contributed to the early industry shakeout and closure of many firms with 8-bit products. Apple co-founder Steve Wozniak explained the need for markets to set standards in terms reminiscent of complexity ideas:

> You’ve got to let end users develop their own standards … when a new market evolves like PCs did, there’s a period of time when you’ve got to let the world go in random directions and eventually it will subside because it wants standardisation. (Langlois, 1992 p.45)

Apple did not make its proprietary technology available as an open standard. [5] This prevented the pioneer from gaining licensing revenues and creating an alliance of companies using its operating system. In the UK, another pioneer, Acorn Computers, also followed a proprietary strategy, not anticipating that in an industry reliant on complementary products, customers would soon shun a minority system incompatible with the industry standard. After the emergence of a dominant design in the form of the IBM PC, the numbers of exits from the industry exceeded the number of entries, resulting in a fall in producer numbers reminiscent of other complex assembled product industries examined by Utterback (1995).

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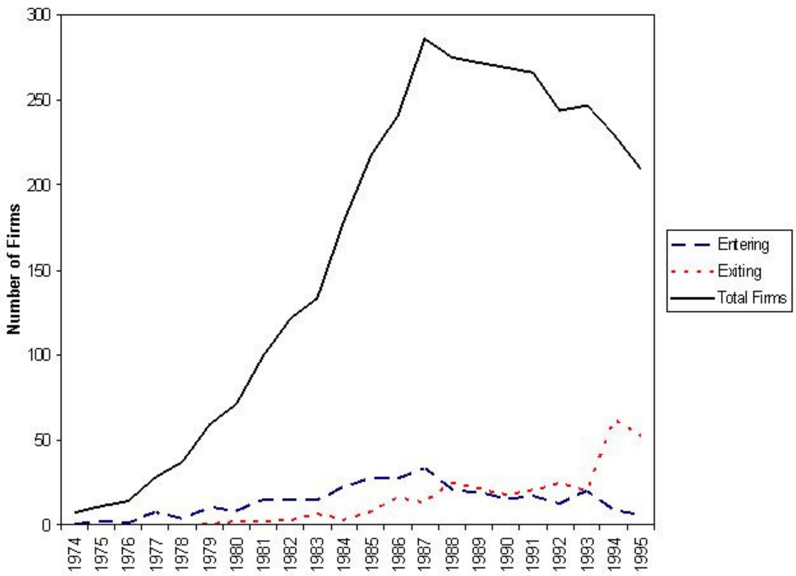
[4] Minicomputers were more accessible than mainframes but still costly and beyond the reach of ordinary consumers and small businesses.

5 Apple’s new CEO John Sculley had previously guarded the Pepsi recipe, though he continued a policy that had been established by Apple’s founders.

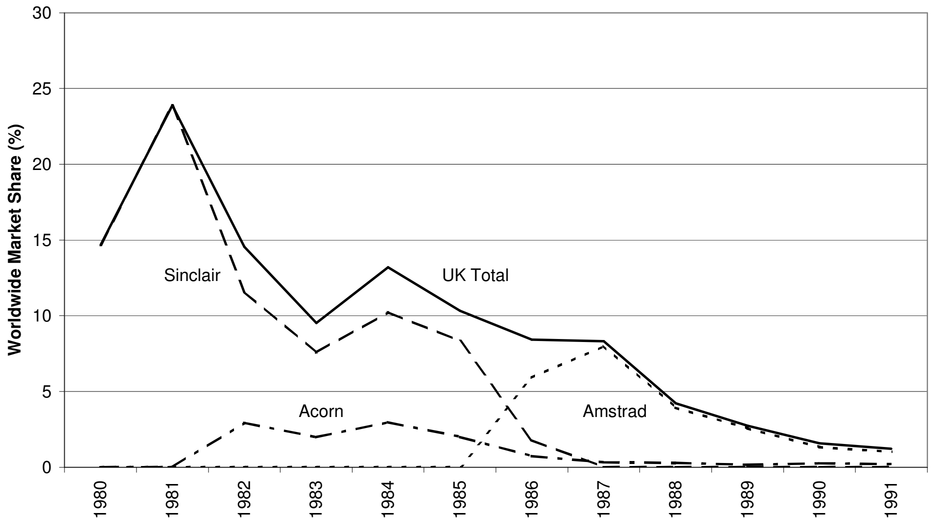



Source: International Data Corporation PC database

Figure 1. Entry, exit and total number of firms, PC sector 1974-1995

IBM had not themselves anticipated the widespread imitation of their PC, which they viewed as a provisional product for a small market. The company secured very limited intellectual property for their system. By outsourcing the PC's operating system from Microsoft without requiring an exclusive license beyond the first 12 months, IBM encouraged other producers to provide peripheral complementary products that enhanced the value of the PC. But they also made it easy for competitors to produce rival products, PC clones, which also worked on Microsoft's operating system using components readily available on the market. The most successful of the companies to introduce PC compatible models, Compaq (founded in 1982) was soon in direct competition with IBM and achieved revenues of over $1,000m by 1987.

In an attempt to regain control of the standard, 1987, IBM introduced its PS/2 Personal System product range with proprietary logic chips and interface standards. IBM ceased production of its previous PC models, but this only encouraged sales of PC clone makers; Compaq's profits tripled in three months in 1987 as exits from the industry rose. But ultimately, it was not the hardware producers that came to dominate the PC industry; hardware and software are interconnected and the user experience is more closely associated with software. By 1987, Microsoft's operating system, MS-DOS, was in use in hundreds of cloned products and had become the basis for a multitude of other software applications. Other companies with operating systems technically superior to MS-DOS found to their cost that the market was locked into MS-DOS. European producers of PCs were soon eliminated in the international market as Figure 2 shows for leading UK producers.

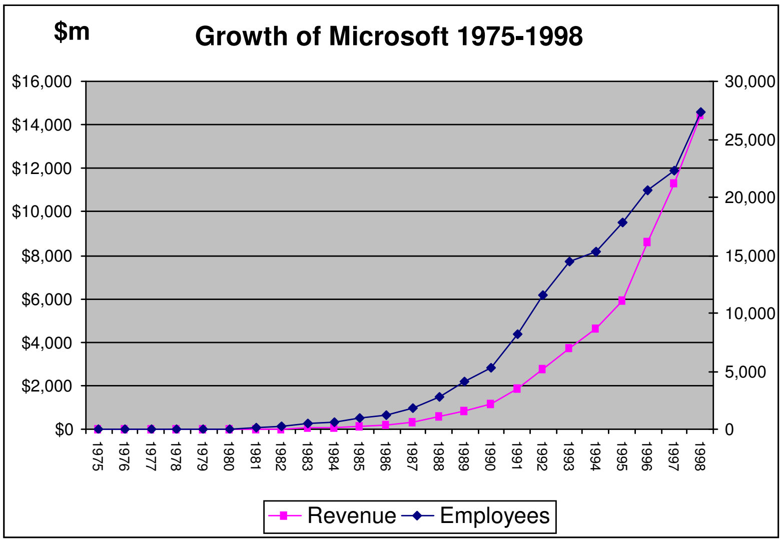



Source: Langlois, 1992 pp. 34-35

Figure 2. Worldwide Market Share of Leading UK Producers of Microcomputers

Microsoft and Intel emerged from the industry shakedown as the dominant players in the industry. Microsoft had begun as a small supplier, but gained crucial leverage through its partnership with IBM when it was able to license the DOS operating system to PC clone producers. Microsoft's revenues grew with the rapid expansion of the PC market, taking off around 1987, the year when the dominance of the PC was established.

As microcomputers reached a wider range of users, ease of use and accessibility became important factors. The Graphical User Interface (GUI), first demonstrated by Xerox in the mid 1970s, was seen as a way of facilitating human-computer interaction, and received clear customer endorsement when successfully implemented by Apple. In response to this perceived threat, Microsoft introduced its Windows product in 1985, a graphical front end to DOS. Maintaining DOS beneath Windows ensured backward compatibility and avoided alienating the established customer base. Though it would be a further five years before Windows could be regarded as a fully functioning GUI, Windows software became a feature of the dominant PC design.




Calculated from Cusumano and Selby, 1996

Figure 3. Microsoft's growth took off with the market expansion of the PC

The personal computer industry provided a market for a wide range of components and complementary products. The PC provides an example of diversity reduction (convergence onto a basic product design) giving rise to extensive variety generation around the new standard. More firms entered the industry because they were confident of a market for products compatible with the standard. Thus, even as diversity diminished in the architecture of the PC and its office software, new generations of improvement were made in components and peripherals. DRAM (dynamic random access memory) for example increased in speed by a factor of 500 between 1975 and 2003, while prices have reduced by a factor of 190,000. Hard disk drives also increased in both speed and capacity while reducing in price, from 5MB and US$2,000 in 1980, to 120GB at US$125 in 2003. Meanwhile printers advanced from monochrome dot-matrix models to low cost colour inkjet and laser printers with similar reductions in cost. The rate of change was enshrined in what has come to be known as "Moore's Law" which has been used since the late 1980s to refer to exponential increases in computing performance.[6] The factors supporting this empirical generalisation were complex. Market forces were operative, but US government funding of information technologies and South East Asian government support for their emerging semiconductor industries, were enabling factors making possible the massive improvement in the performance and yield of computer chips and increasing miniaturization.

6 In 1965, Gordon Moore, then a Director of Fairchild Semiconductor, observed that the number of components on a cost-effective silicon wafer had doubled each year since 1959. He predicted that this rate of increase would continue for a further 10 years. In 1975, Moore extended his prediction, but this time referred to the maximum complexity over 2 year periods. The period of the effect is frequently quoted as 18 months (e.g. EC, 2000; Cringely, 1996).

## 2.3. A Critical Transition to Connectivity: Electronic Messaging

By the early 1990s, the computing power of the desktop PC had reached a level achieved only by minicomputers and workstations a decade earlier. Largely as a result of the advances in IT supported by these developments, a critical shift took place in the key attribute of PCs. Improvements in memory and processing speed had become required rather than winning attributes for sales, since competing PC makers used the same semiconductor chip suppliers. It was the connectivity of PCs that provided opportunities for meeting user needs in a new way, leading to the emergence of a new communications sector, electronic messaging.

The standardisation of communication protocols was first required for PCs to become the vehicle for a new form of electronic communication. TCP/IP protocols had been developed as part of the US Military's ARPANet, the origin of the Internet.[7] These had become the standard for connecting PCs to local computing system servers and servers to each other. The development of the World Wide Web facilitated Internet usage as it provided a common set of protocols for access and storage of information through the Internet. The Web was made possible by small amounts of European public sector funding at CERN and discretionary time being accorded to one employee, Tim Berners-Lee (Berners-Lee and Fischetti, 2000). He saw that uniformity of standards was needed to support new forms of diversity. His entrepreneurial efforts were directed towards social rather than commercial returns. The Web illustrates the unintended impact of public sector funding in enabling work that was required to achieve standards but would not offer a commercial payback.

Once again the role of new entrants in taking up opportunities for this form of variety generation is demonstrated. Lack of insight among newly established players can be observed in the failure of Microsoft and IBM to anticipate the importance of the Internet. As in the case of the microprocessor and the microcomputer, new ventures were the first to seize new opportunities opened by the ease of communication between users' microcomputers. Netscape and Cisco Systems were set up by entrepreneurs who transferred technologies that had been developed in universities. Netscape (founded in 1994 as Mosaic) was a spinout from the government-

[7] TCP/IP stands for Transfer Control Protocol/Internet Protocol, 2 sets of rules that allow computers and networks to communicate effectively. The ARPANET originally used NCP, for communication, but the TCP was devised to enable ARPANET to communicate with other networks, i.e. the early Internet. It was adopted by the US DoD in 1980 and was introduced to the ARPANET in 1983 (Zakon, 2003).

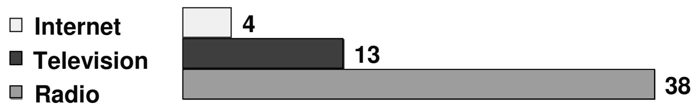
supported computer science department at Michigan University and pioneered a graphical web browser. Cisco was a spin-out from Stanford based on federally funded LAN research. It provided the servers and routers necessary for large scale PC network infrastructure. Netscape was one of the first companies to base its success on freeware. Nurtured in the 'gift culture' of the government funded IT community, Netscape's entrepreneurs were among the first to see that propagation might require giving it away initially and earning returns on enhancements or future related products.

The technology and standards underpinning the Internet and the World Wide Web (WWW) serve as enablers for a wide range of applications, from e-commerce to online gaming. Connectivity extended the use of the PC beyond word and data processing to the provision of a data and communications portal. In the office, more people were using a computer for internet-based tasks (including email) than for word processing or Desk Top Publishing and user-to-user contact through electronic messaging proved to be the most common use of the Internet (BLS, 2001).

After nearly twenty years in which electronic mail had been used by professionals to communicate with each other, PCs had the computer power and the Internet infrastructure was in place to make it possible to link users to each other on a massive scale. Pioneering firms experimented with business models aimed at providing this new form of communication from 1993. Influenced by Netscape, Hotmail's entrepreneurs conceived the idea of providing free e-mail accounts on the Internet leaving users to set up their own account with Internet Service Providers, so reducing Hotmail's costs to the point where, with revenue from advertisers, they could provide a free service. By 1997, four hundred further new entrants swarmed into the sector as participants in the Internet boom of the late 1990s (Hugo and Garnsey, 2002).

Established companies did not initially detect that the Internet had commercial potential as significant if not more so, than hardware and applications for isolated PCs.[8] But the expansion of email communication was unprecedented. Between 1993 and 1997 use expanded to reach a reputed 50 million. Hotmail alone acquired seven million users between 1996 and 1997.

8 Until 1995, Internet use was limited to non-commercial applications, though some commercial activities had begun in the early 1990s.




Source: Meeker, 1996

Figure 4. Time Taken to Reach 50 Million Users

As soon the success of the Internet pioneers came into view, Microsoft was quick to engage in Schumpeterian imitation, pursuing its policy of acquiring new entrants with promising technologies. The best known was Hotmail, acquired for $400m in 1997. Adapting the concept of providing free software in order to attract customers, Microsoft soon bundled its web browser with Windows software. Since Microsoft software was standard with PC purchases, Microsoft's browser, Internet Explorer, effectively put Netscape out of business.

## III Discussion: Unique Developments and Common Processes

We return to the questions raised in the introduction concerning linkages between variety creation, selection and propagation processes and ask them of the ICT sector. A complexity approach reveals a persistent dynamic operating between the diversity of user needs – met by multiple technical solutions – and the uniformities that make interchange possible. This dynamic interplay between variety and uniformity has provided the impetus for complementary and compatible innovations. As complementary technologies matured, increasing returns promoted an economic boom, but as asynchronies built up they precipitated the ensuing slump, a recurrent feature of rapid technological advance.

### *3.1. The agents of variety generation and the origins of their knowledge*

Co-evolution did not occur immediately. Unrelated experiments took place around an enabling technology before producers came up with products at a price and with specifications attractive to consumers. Entrepreneurial firms hit upon innovative solutions as they sought to exploit business opportunities in the face of stringent resource constraints. Early periods of ferment of this kind have been identified in many other industries (Utterback, 1994; Nairn, 2000). Variety generation was in each of these examples made possible by new knowledge developed with the support of public funding and made available in the public domain. Entrepreneurs with relevant experience and expertise were able to perceive and pursue the opportunities offered by knowledge newly entering the public domain.

A pool of knowledge representing an investment of time and effort forms outside the market arena for two main reasons. Firstly, scientific knowledge undergoes its own evolutionary processes and advances create an independent problem-solving potential that may have unexpected market applications. Secondly, the payback anticipated from funding the commercialisation of research seldom attracts market investors, who look for earlier and more certain returns on capital.[9] In the case of transistors, microcomputers and electronic messaging, established companies had access to scientific and technological knowledge, and in some cases involvement in their development, with support from public funds. However, entrepreneurial ventures had no vested interests in prior technologies and ways of organizing business, and had no existing customers to alienate or reputation to sully by offering a product based on immature technology.

In semiconductors, technological performance depended on a pool of resource provided by the public sector, no less than on market forces. Although the transistor, integrated circuit and microprocessor were invented in private companies, Bell Labs, Fairchild and Intel, there were years of technical expertise funded by government behind their inventions. Major federal contracts supported development work and the Small Business Innovation Research programme (SBIR) made it possible for new entrepreneurial firms to access this funding (Wessner, 2003). Shockley, Fairchild and others employed large numbers of PhDs trained in universities supported by government funding. At Intel, the creator of the microprocessor, Ted Hoff, came straight from research at Stanford. The US defense department supported scientific and technical education in universities on an unprecedented scale (Lowen, 1997).

The microcomputer is often cited as an industry that was the product of pure enterprise without government subsidy (Fong, 2001). But here too the costs of developing the technologies that went into such features as the graphical user interface (GUI), the mouse and the local area network (LAN), were not borne wholly by the market. The Defense Advanced Research Projects

[9] This argument is by no means universally accepted. For instance, Kealey (1996) argues that government funding displaces commercial funding in a ratio of greater than 1:1. He suggests that the majority of government funding of science is only necessary because it is now the accepted norm. The evidence of the three cases presented here indicates that government funding played an important part in the generation of variety.

Agency (DARPA) was heavily involved. DARPA provided extensive support for selected computer science departments throughout the US, including UC Berkeley and Stanford. DARPA funds made possible the accelerated development of graphics through the sponsorship of the CAD industry and through support for the computer scientists who developed GUI advances and LANs (Hafner and Lyon, 1996). DARPA employed and supported the knowledge generation of many of those who were later active in Xerox PARC in Palo Alto, the home of developments that inspired Apple's Macintosh computer and ultimately Microsoft Windows (Fong, 2001). Much DARPA related business was carried out at Xerox PARC itself (Hafner and Lyon, 1996 p.238). Without Cold War defense funding, the microcomputer industry could not have grown so quickly. A pool of knowledge funded outside the market and accessible to new ventures compensated for the short-term focus of capital markets. The success of these sectors made possible the expansion of commercial venture capital.

Both the Internet and the World Wide Web, which were necessary underpinnings for online electronic messaging, emerged from government-funded activities, the former from the US ARPANET, and the latter from the work of Tim Berners-Lee at CERN. Again, it was entrepreneurs who identified and acted to exploit the opportunities in a variety of ways apparently not foreseen by the original developers and funders. In these sectors, variety generation was facilitated by historically and culturally specific conditions. The San Francisco Bay area provided a creative and unconventional culture that encouraged innovation. The 'gift culture' in IT, which stimulated technology diffusion, was made possible in part because US defense expenditure to provided munificent resources for IT development during the Cold War. The anti-trust tendencies of the judiciary led large companies to make available innovative technologies, including RISC and UNIX, for licensing on favourable terms (Mowery and Rosenberg, 1998).

Scientific knowledge created with government support was not sufficient to create an IT economy. This is illustrated by the contrast with the Soviet Union, where the absence of incentives and market mechanisms for transforming scientific advances into industrial innovation prevented the command economy's transition to the information age (Mowery, 1996). However, market mechanisms represented "…only one level and mode of selection" (Metcalfe, 1994 p.29). Cultural factors, government policy and institutions that included the universities and standards setting bodies were part of the co-evolutionary process from which complementary innovations emerged in the US. In Japan, South Korea and Taiwan, public support for industrial research and production made possible the increases in corporate production capacity and skills that raised yields and sustained rates of improved performance of semiconductors alongside massive reduction of costs (e.g. Kim, 1997). Asian public expenditure helped sustain Moore's Law.

### *3.2. Feedback Mechanisms Connecting Variety Generation, Selection and Propagation*

#### 3.2.1. User-producer interaction and learning

Technologies are not simply selected in the marketplace on the basis of pre-given price and quality attributes, but are constructed and refined through a collaborative learning process (Bijker, Hughes and Pinch, 1987). Early input-output computing kits like the Altair became the personal computer through user involvement. Learning on the part of providers and users continue to shape developments as markets mature. Early customers for a new product, looking for a new solution, are prepared to accept relatively unreliable products with complex interfaces (Rogers, 1983). As a wider range of users is reached, usability and reliability become key requirements. In the PC sector early adopters used the machines to write their own programs but by the early 1980s pre-packaged applications took over in consumer markets.

#### 3.2.2. Competitive selection around standards

In networked industries, users benefit as the number of users of an innovation increases.[10] Katz and Shapiro identified 3 sources of consumption externalities from which users benefit in networked industries. (1) The direct physical effect of the number of purchasers, as might be found with a telephone system where utility increases with the number of connections. (2) Indirect effects such as the availability of associated products, as might be seen with software for a particular type of computer hardware, or pre-recorded tapes for videocassette recorders. (3) Support effects, whereby the quality and availability of post-purchase service depends upon the experience and size of the service network (Katz and Shapiro, 1985). If these benefits are to be experienced, products must be compatible with each other, calling for agreed, imposed or *de facto* technical standards.

[10] Bob Metcalfe hypothesised that the utility of a network was proportional to the square of the number of users (Rohlfs 2001). Rohlf points out that this 'law' assumes that the value that users derive from a networked product or service is the same for all users, but in reality some users will derive more value than others and links with different users have differential value. While the insight is valid this statement of it is incorrect and likely to overstate the value of large networks.

There are also advantages in common focus on a given set of production problems. Pressures to standardize the wide range of new variants launched by the early experimental phase of a newly commercialised technology result in the emergence of a dominant design of an assembled product, as in the 'keyboard, monitor, processor' features of the PC. This is pivotal for the formation of an industry in the conventional sense of a set of producers producing competing products (Utterback, 1994; Munir and Phillips, 2002). A related development is a set of technical standards that promote interoperability. These include protocols for connectivity in telecommunications and the media or common interfaces modes in hardware and software.[11] In the three sectors examined, variety generation and selection interacted around the adoption of technical standards. Once a specific technical standard is selected, switching costs are created for consumers who have invested funds and knowledge in that standard. A path dependent lock-in of this kind helps to explain why the market does not always select the best performing technology (Arthur, 1990; Rohlf 2001.43).

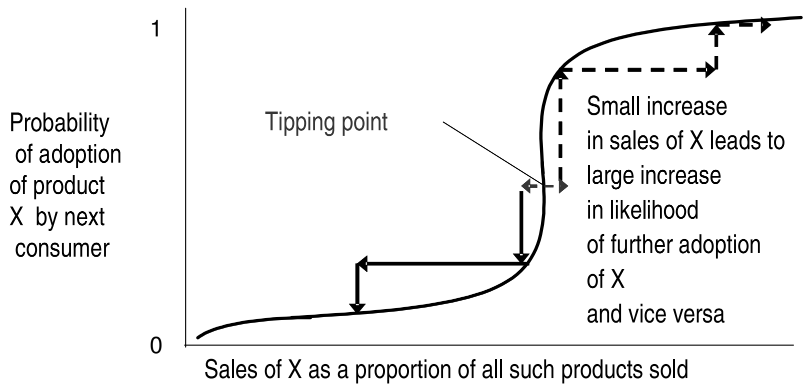
### 3.2.3. Network Externalities Reinforce Selection

In the network products we have reviewed, the need for products to be compatible or support interoperability was a critical factor in determining the survival of firms offering early experimental designs. The emergence of a preferred solution changes the competitive environment to provide an advantage to those firms that adopt the standard as compared with those that have non-standard products (Tegarden *et al.*, 1999). For products in these markets, selection and propagation are not empirically separable. The rapid propagation of winning products results in the selection of these products by new adopters, with increasing sales tipping the likelihood of further sales in the winners' direction.

The combination of selection and propagation acts as a self-reinforcing process so that the market power of dominant players is increased. In theory, when network effects operate at the limit, there can be a change in phase state, from competing technologies to the emergence of a clear winner. This occurs as new users head for what becomes the market's preferred technology and some existing users also move over to this emerging dominant standard.

[11] Connectivity protocols include TCP/IP for local area networks and IEEE 802.11 for wireless ("wi-fi") networks. Physical connections such as PCI, SCSI and USB provide hardware interfaces; device drivers and programming languages provide the interface between software and hardware.

A rapid shift of this kind occurred in the emerging PC industry. An incremental increase in sales of IBM PC software produced a cascade effect, leading to the selection of the IBM PC at the expense of Apple products. In 1982, software for Apple had made up about 85% of the microcomputer software market but it fell to 35% within a year with the rapid expansion of




Source: adapted from Agliardi, 1998 p.62

Figure 5. Network effects illustrated by Probability of Adoption Curve

software applications for the IBM PC. Apple's market share halved between 1981 and 1984 and continued to fall, while IBM's expanded to 33% of the global market by 1984 (Gabel, 1991 p.24). As early as 1987 over 80% of the market was compatible with the IBM PC (Grindley, 1995 p.140). Buyers' preference was the overt mechanism of selection in the PC sector which led to the elimination of non-compatible systems such as Apple's.

### *3.3. Path dependence and the Acceleration of Innovation*

Innovation in the ICT sector took the form of specialist niche activity, with these niches providing a favourable environment for new entrant growth. As technologies matured, certain niches expanded to become mainstream markets attracting complementary activity. Those producers of bandwagon products that acquired a massive user set enjoyed great competitive advantage. But some niches survived where the needs of particular markets were met.

The increasing diffusion and interoperability of PCs resulting from earlier advances drove the emergence of electronic messaging, enabled by the Internet and World Wide Web. Further progress in PC processing and memory enabled advances in other hardware and software sectors, notably telecommunications and image processing. A new conjuncture in computer and communications was to be seen in mobile devices and handheld computers. In each of these cases, technological advances built on what had gone before, in the path dependent mode created by cumulative feedback processes.

The pace of change was accelerated by interactivities, increasing the difficulty of predicting and synchronising innovative products, services and modes of provision. Schumpeter argued that the swarming of innovations was responsible not only for "leaps and bounds of progress" but also for setbacks "carrying in their wake not only the primary disturbance, inherent in the process, but a whole string of secondary ones and the possibilities ... of crises." (Schumpeter, 1928 p.384) He recognised that difficulties in assimilating bursts of disruptive innovation can set off periodic disturbances in the economy.

As complex dynamic systems, industries are prone to surge effects in the intensity of innovative activity. Such surges provide impetus to technological progress, but they create asynchronies and disturbances with unpredictable outcomes. There are historically specific factors at work. In the late 1990s, when stock market speculation led to the boom and bust of Internet ventures incentives exerted by increasing use of share options for managers and the rapid dismantling of regulatory controls were among the precipitating factors (Stiglitz, 2003). Speculative bubbles have in the past arisen as returns from new forms of investment rose well above the other sources of return on capital (Nairn 2000). Even once it was clear that share values of technology ventures were out of line with possibilities for real returns, investors feared losses from pulling out too soon (Cassidy, 2001). Events then precipitated a sudden shift in investor sentiment through tipping effects, as demonstrated by the NASDAQ Index before and after the Millenium.

When a speculative bubble bursts it is more difficult for new projects to obtain funding, so bringing about a lull in variety creation. The disturbances predicted by Schumpeter spread throughout telecommunications industry and also reduced funding for biotechnology ventures post-Millennium.


Source: Yahoo Finance http://finance.yahoo.com

Figure 6. NASDAQ Exchange Monthly Closing Values 1984-2002

## IV Diversity, Uniformity and Innovation

Despite contrary historical evidence, we tend to assume that the future will be like the past. A complexity approach leads us to expect that continuity will be challenged by reactions to current conditions and consequent feedback effects. In this final section we explore some of the difficulties of predicting co-evolutionary developments when complex dynamic processes are at work.

The Darwinian evolution of life forms takes place unimaginably slowly, the evolutionary mechanisms of variety generation, selection and propagation occurring independently of each other. The random emergence of new variants and the elimination of those that are less adaptive takes place over 'deep time'. Survival rewards for mutual accommodation have been found to underlie co-evolution (Goodwin, 1994). In the natural world, collaboration is not pursued because its benefits are envisaged, but through blind responses that sustain mutual advantages.

In contrast with the Darwinian process, advances in IC technologies have been occurring ever faster as evolutionary mechanisms in ICT have become more closely coupled. While there are reasons to expect the acceleration of innovation to continue, other considerations remind us that the continuity of earlier patterns is far from inevitable and that innovation does not equate to diversity generation. Successful innovations are the product of competition, which is essentially a variety-reducing force. The further generation of new forms is needed if diversity, along with future innovation, is to be sustained.

Factors favourable to the sustained pace of innovation relate above all to the level of technological knowledge that has been reached and to inherent features of ICT. There have been cumulative processes advancing the depth and range of knowledge about electricity from the $18^{th}$ century, with advances building on prior knowledge as science and practice broke through earlier barriers. From the beginning of the twentieth century, when Hertz's discoveries fed Marconi's efforts at broadcasting radio waves, through to mid-century advances in solid state physics, knowledge accumulated so that by the end of the century it had reached a critical mass that made possible an effervescence of technological advance. Complementary innovations were forthcoming in anticipation of the positive selection exerted by demand. Although some co-evolving developments were unintended (e.g. text messaging along with mobile telephony), overt collaboration has been common. We have seen that early selection of a variant by the market fostered its propagation as network effects took hold. Amplifying forces created dominant standards which provided the basis for further variety through complementary innovations.[12] These coupled evolutionary mechanisms were self-reinforcing.

Unique features of information and communication technologies contributed to the rapid rate of innovation: their generic nature, scalability and modularity. ICTs have uses across multiple industries and sectors. Increasing returns in software production make software innovations highly scalable. The modularity of ICT innovations is conducive to further innovation because it allows diverse products and infrastructures to be interoperable through the use of interfaces that promote connectivity. There remain myriad markets that have yet to be penetrated by ICT, especially in developing countries, which offer prospects for new applications if technological capabilities and market needs can be coupled. Cost reductions in mobile telephony represent a striking illustration of this possibility.

Moreover it does not require radical advances in knowledge to give rise to radical innovations. Incremental innovations that are brought together from different domains may result in new species of technology. Different streams of technology, each developing gradually, can give rise to major advances. For example, gradual advances in magnetic data storage and in optical

[12] An example of cross-fertilization is provided by storage devices developed for photographic images which turn out to have applications for other types of data files.

signalling were combined in established companies to provide the basis for video recording. Applications of newly combined technologies to entirely new domains of use can sustain innovation.

### *4.1. Uncertainties affect the pace of innovation*

Forces favourable to continuing rapid innovation are not the only trends in evidence. There are counter forces at work that make outcomes unpredictable. "The difference between systems that are predictable and systems that are not predictable lies in the numbers of degrees of freedom they possess … (Bass, 1999, p.236). Degrees of freedom are all the greater when industries have no enduring structure or boundary, contrary to assumptions in industrial economics (Munir and Philips, 2002). In ICT industries in particular, the boundaries of industries were reconfigured as new products and sectors were spawned, through developments that encompassed workstations, hand held devices, Internet-based services and multiple applications in telecommunications.

Among forces that could counter rapid innovation are the intractable requirements of synchrony as industries mature and interconnect. On the supply side, the synchronization required for the co-evolution of technologies is continually challenged by delays between design and market readiness, and lags between investment and returns from sales. Market signals are celebrated for spontaneous coordination of supply and demand. They are less effective at re-synchronizing temporal de-couplings. The stock market crash of the Millennium points to asynchronies that are not corrected by stabilizing market mechanisms but are instead exacerbated by their positive feedback effects. In financial markets herd behaviour prevails and the real economy pays for re-coordination through crisis and slump. The price may rise with the proliferation of derivatives which have increased the liquidity that facilitates exchange at the cost of potentially greater dislocating effects.

The enabling conditions of the late 20$^{th}$ century had a largely unanticipated impact on innovation. Federal investment in science was expected to foster innovation in large companies through a linear process in which scientific research eventuated in commercial and social returns (Bush, 1960). Instead, the most important innovations of the information revolution were made by resource-constrained new entrants. This unintended outcome of policy was the result of contingent conditions that are not self perpetuating. Selection processes are increasingly supporting big laboratories and established paradigms rather than small innovative teams and new ideas. The bureaucratization of science and intellectual property arrangements that benefit established players could endanger sources of variety and the selection of new variants. In the US, the post World War II judiciary applied an anti-trust regime that made it possible for new entrants to challenge established players (Mowery and Rosenberg, 1998). More recently, established players who could defend their patents have been favoured by intellectual property arrangements and rulings. Pressures on companies to focus on short-term share price gains have also increased (Stiglitz, 2003). The slump following the 'correction' to share prices in 2000 greatly reduced the availability of venture capital for experimental new entrants. Such risk averse investment conditions make it difficult for new entrants to play the role of agent of change.

In Europe, the standardization of selection conditions has been a goal of policy. These are less favourable to the rise of new species of activity than diverse economic habitats providing a variety of different selection conditions. Market selection may not provide independent mechanisms for variety generation when expected returns from a known set of selection forces determine the variants launched on the market. The prospect of low returns have limited the extent of innovation in drugs for common diseases and ICT suited to conditions in low income economies.[13] Rather than becoming more equal, the distribution of income within and between countries has become less equitable, limiting the purchasing power of potential consumers of ICT innovations and creating the 'digital divide', a societal segregation between those with access to ICTs and those without. A key influence on diversity will be new selection conditions in emergent economies and the response of innovators there to information technologies.

Physical limits to improvements in technical performance have brought waves of innovation to an end in the past (Freeman, 1982). But before such limits are reached, there are other factors at work that can alter the pace of innovation as technologies and industries mature, notably the lock-in of consumers to dominant technologies and asymmetries of market power. Established firms can use returns from past successes to innovate. Both Microsoft and Intel, alert to potential competition, have attempted regular product updates and innovations. But incumbent firms have only rarely shown the capability and incentive to introduce radical innovations (Utterback, 1994; Nairn, 2000). It was not until pioneering new entrants had demonstrated the returns to be

[13] Geographic diffusion and diversity of selection regime have taken on new impetus with the growth of the Indian and Chinese economies.

obtained from microcomputing and the Internet that incumbents imitated their initiatives.[14] As the Xerox PARC case illustrates, even established companies promoting advanced R&D faced inertia that prevented assimilation of the knowledge they generated in their own labs (Rumelt, 1995).

Along with the acquisition of more innovative entrants, the most likely source of major innovations from incumbent companies is the application of a known technology to a new domain, often through new combinations (Levinthal, 1998).[15] But there are factors relating to technical standards and strategic realities that affect the propensity for breakthrough innovation in established corporations. Owners of proprietary standards tend to inhibit innovations that could threaten their position. Modularity of design allows diversity of provision to coincide with standard interfaces, so opening up new domains of application, as in retail payment systems. But as Penrose pointed out, there are strategic limits to the new directions in which established companies can move (Penrose, 1959). Companies with reputations at risk from uncertain new products prefer to manage risk by using tried and tested solutions, or incremental variations thereon. Groundbreaking innovations are by their nature risky and are adopted only in exceptional conditions by corporate decision makers (Christensen, 1997). Managers under pressure to demonstrate short-term share price gains are unlikely to embrace uncertain new technology paradigms.

In sum, the evidence we have examined reveals the extent to which market exchange stimulates both the multiple variants of goods and services that meet diverse needs and the uniformities that make exchange possible. Amplifying processes reinforce emerging concentration and asymmetries of market power. Kauffman has shown that as networks mature and become interlocking, there is a reduction in the diversity of outcomes (Kauffman, 1996). Whether or not this will apply to ICT technologies depends on the interaction of countervailing forces. The close coupling of variety generation, selection and propagation has accelerated innovation in ICT over the period examined, but this dynamic has depended on a contingent set of favourable conditions, including long-term investment in science and technology and incentives for technical entrepreneurs. Policy can be directed towards fostering favourable conditions but these are much more specific and difficult to provide than an ill-defined ‘climate of enterprise’.

[14] Although IBM established the standard for the PC, it did not enter the market until the basic technology and architecture had been tested by more entrepreneurial ventures. This is consistent with the type of risk-reducing strategy that might be expected from a large incumbent firm.

In the twentieth century, government policies in the home of free markets helped to shape the very conditions of supply and demand that gave rise to innovations. Advances in science, the output of skilled technologists and an intellectual property regime favourable to innovation, were among the conditions of supply formed by US policy. Demand was influenced by public procurement, regulation and fiscal incentives, among other factors (Stiglitz, 2003). It was an unintended consequence of Cold War defence policies that they created munificent conditions not only for science but for technology-based enterprise in the USA.[16] Radical innovation in the private sector resulted from the application of new knowledge made available in the public domain by massive public funding on IT research in US companies and universities (Mowery and Rosenberg, 1998). In particular, government funding supported the advance of IT from invention to market-ready applications, bridging the gap between R&D and market, paving the way for profitable venture capital and public listings.

Policies that promoted ICT reveal that supply and demand do not operate as market forces independently of government measures and institutions. Supply and demand are the outcome of all the complex dynamic forces of selection and variety generation. These include the institution-based and publicly funded transactions that allocate resources, alongside the choices of private consumers and producers. There is no such entity as the market. Market signals are the emergent properties of complex processes of exchange.

While the US Cold War policies inadvertently enabled micro-diversity in ICT, this diversity can be deliberately fostered in other spheres. For example, current market conditions do not provide the capital required for the long term development and commercialization of innovative clean technologies. But the experience of ICT indicates that if environmental degradation is to be counteracted and the necessary conditions created for rapid innovation in clean technologies, public campaigns in support of the natural environment need to be funded as an all out war. The record shows that overcoming incumbent and consumer inertia can only be achieved when selection conditions counteract asymmetries of power and wealth, allowing scope for initiatives at the micro-level enabled by public funding.

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[15] As Darwin emphasized, many branches of the tree of life were eliminated by selection forces, but immense variety was possible among the remaining branches.

[16] The US military provided an intermediary IT customer/funder in cases where market assimilation would have been too slow to provide incentives to invent and develop an innovation.

Ferment in the realm of knowledge is a critical feature of radical innovation. The progress of ICTs across generations of innovation shows that investment in knowledge yields returns more extensive than the capture of gains by originators. Entrepreneurial innovators are stimulated by new ideas and often act on them prior to shifts in supply or effective demand. Path breaking entrants anticipate and respond to selection forces in a different manner from incumbents. It is because they have much less to lose that entrepreneurial ventures pursue opportunities overlooked by better resourced players. Although the rate of failure of new entrants is wasteful, this failure constitutes the overhead required to generate diversity. Experimental entrants give rise to distributed forms of innovation, the costs of which are mitigated by serendipity and the triumph of the unexpected.

**Bibliography**


Agliardi, Elettra (1998), *Positive Feedback Economics*, Basingstoke: Macmillan.

Arthur, W.B. (1990), 'Positive Feedbacks in the Economy', *Scientific American*, 80, 92-99.

Barney, Jay B. (1997), *Gaining and Sustaining Competitive Advantage*, Harlow: Addison-Wesley.

Bass, Thomas (1999), *The Predictors: How a band of maverick physicists set out to beat Wall Street*, London: Penguin.

BBC (2000) 'Text messaging grows up', http://news.bbc.co.uk/1/hi/uk/916337.stm

Berners-Lee, Tim and Mark Fischetti (2000), *Weaving the Web: the past, present and future of the World Wide Web by its inventor*, London: Texere.

Bijker, Wiebe E., Thomas P. Hughes and Trevor J. Pinch (1987), *The social construction of technological systems: new directions in the sociology and history of technology*, London: MIT Press.

BLS (2001), 'Computer and Internet Use at Work in 2001', www.bls.gov/news.release/ciuaw.nr0.htm

Both, David P. (2002), 'A Short History of OS/2', http://www.databook.bz

Bush, V. (1960) *Science: The Endless Frontier*, Washington: National Science Foundation.

Cavalli-Sforza, Luigi L. (2001), *Genes, Peoples and Languages*, London: Penguin.

Chandler, Alfred D. (2001) *Inventing the Electronic Century: the Epic Story of the Consumer Electronics and Computing Industries*, New York: Free Press.

Cringely, Robert X., (1996), *Accidental Empires*, London: Penguin.

Cusumano, Michael A. and Richard W. Selby (1996), *Microsoft Secrets*, London: HarperCollins.

Darwin, Charles (1985), *The Origin of Species*, London: Penguin.

Downes, Larry and Chunka Mui (1998), *Unleashing the Killer App*, Boston: Harvard Business School Press.

EC (2000), *European Competitiveness Report 2000*, 1823.

Fong, G.R. (2001), 'ARPA Does Windows: The Defense Underpinning of the PC Revolution', *Business and Politics*, 3 (3), 213-237.

Freeman, Christopher (1983), *Long Waves in the World Economy*, London: Butterworth.

Freeman, C. (1995), 'The National System of Innovation: Historical Perspective', *Cambridge Journal of Economics Special Issue on Technology and Innovation*, 19 (1), 5-24.

Gabel, H. Landis (1991), *Competitive Strategy for Product Standards*, London: McGraw Hill.

Gould, S.J. (1980), 'Is a New and General Theory of Evolution Emerging?', *Paleobiology*, 6 (1), 119-30.

Grindley, Peter (1995), *Standards strategy and policy*, Oxford: Oxford University Press.

Grove, Andrew (1996), *Only the Paranoid Survive: How to Exploit the Crisis Points that Challenge Every Business and Career*, London: HarperCollins.

Hafner, Katie and Matthew Lyon (1996), *Where Wizards Stay Up Late: the origins of the Internet*, New York: Simon and Schuster.

Hugo, Oliver and Elizabeth W. Garnsey (2002), 'Hotmail & Co.: The Emergence of Electronic Messaging and the Growth of Four Entrepreneurial Entrants', in Wim E. During, Raymond P. Oakey and Saleema Kauser (eds), *New Technology-Based Firms in the New Millennium*, Amsterdam: Pergamon.

Katz, M. and C. Shapiro (1985), 'Network Externalities, Competition and Compatibility', *American Economic Review*, 75, 424-440.

Kauffman, Stuart A. (1996), *At Home in the Universe: The Search for Laws of Self-Organization and Complexity*, London: Penguin.

Kealey, Terence (1996), *The Economic Laws of Scientific Research*, Basingstoke: MacMillan.

Kim, L. (1997), 'The Dynamics of Samsung's Technological Learning in Semiconductors', *California Management Review*, 39 (3), 86-100.

Langlois, R.N. (1992), 'External Economies and Economic Growth: The Case of the Microcomputer Industry', *Business History Review*, 66, 1-50.

Levinthal, D.A. (1998), 'The Slow Pace of Rapid Technological Change: Gradualism and Punctuation in Technological Change', *Industrial and Corporate Change*, 7 (2), 217-247.

Lowen, Rebecca S. (1997), *Creating the Cold War University: The Transformation of Stanford*, Berkeley: University of California Press.

McKelvey, Maureen D. (1996), *Evolutionary innovations: the business of biotechnology*, Oxford: Oxford University Press.

Meeker, Mary (1996), *The Internet Advertising Report*, Morgan Stanley US Investment Research.

Metcalfe, J.S. (1994), 'Technology Systems and Technology Policy in an Evolutionary Framework', *Cambridge Journal of Economics*, 19, 25-46.

Metcalfe, J. Stanley (1998), *Evolutionary Economics and Creative Destruction: The Graz Schumpeter Lectures*, London: Routledge.

Moore, G.E. (1965), 'Cramming more components onto integrated circuits', *Electronics*, 38 (8), 114-117.

Moore, G.E., 1975, ‘Progress in digital integrated electronics’, *IEEE International Electron Devices Meeting, IEDM Technical Digest*, 11-13.
Moore, James F. (1996), *The Death of Competition: Leadership and Strategy in the Age of Business Ecosystems*, Chichester: Wiley.
Mowery, David C. (1996), *The International Computer Software Industry: A Comparative Study of Industry Evolution and Structure*, New York: Oxford University Press.
Mowery, David C. and Nathan Rosenberg (1998), *Paths of Innovation: Technological Change in 20th Century America*, New York: Cambridge University Press.
Munir, K. and N. Phillips (2002), ‘The concept of industry and the case of radical technological change’, *Journal of High Technology Management Research*, 13, 279-297.
Nairn, Alasdair G.M. (2002), *Engines that Move Market: Technology Investing from Railroads to the Internet and Beyond*, New York: John Wiley and Sons Inc.
Rohlfs, Jeffrey H. (2001), *Bandwagon Effects in High-Technology Industries*, MIT Press MA, London.
Rogers, Everett M. (1983), *Diffusion of Innovations*, New York: Free Press.
Rosenberg, Nathan (1994), *Exploring the Black Box, Technology, Economics, and History*, Cambridge: Cambridge University Press.
Rumelt, Richard P. (1995), ‘Transformation and Inertia’, in Cynthia A. Montgomery (ed.), *Resource-Based and Evolutionary Theories of the Firm: Towards a Synthesis*, London: Kluwer.
Schumpeter, J.A. (1928), ‘The Instability of Capitalism’, *Economic Journal*, 38, 361-386.
Stiglitz, Joseph (2003), *The Roaring Nineties*, New York: WW Norton.
Tegarden, L.F., D.E. Hatfield and A.E. Echols (1999), ‘Doomed from the start: what is the value of selecting a future dominant design’, *Strategic Management Journal*, 20 (6), 495-518.
Utterback, James M. (1994), *Mastering the Dynamics of Innovation*, Boston: Harvard Business School Press.
Wessner, C. (2003), ‘Sustaining Moore’s Law and the US Economy’, *Computing in Science and Engineering*, 5 (1), 30-38.
Wolfe, T. (1983), ‘The Tinkerings of Robert Noyce, How the Sun Rose on the Silicon Valley’, *Esquire Magazine*, December, 346-374.