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Technology-push, demand-pull and the shaping of technological paradigms – Patterns in the development of computing technology*

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Abstract. An assumption generally subscribed to in evolutionary economics is that new technological paradigms arise from advances is science and developments in technological knowledge. Further, demand only influences the selection among competing paradigms, and the course of the paradigm after its inception. In this paper, we argue that this view needs to be qualified and modified. We demonstrate that, in the history of computing technology in the 20th century, a distinction can be made between periods in which either demand or knowledge development played the bigger role in shaping the technological paradigms. In the demand enabled periods, new technological (sub-)paradigms in computing technology have emerged as well.

Keywords: Technological paradigms – History of computing – Demand-pull – Technology-push

JEL Classification: L96, O33

1 Introduction

Important in understanding the development of technological paradigms are the effects of push and pull, or supply and demand, factors. The field of technology studies, discussing this issue in the 1970s, finally came to the conclusion that both were important for innovation and the development of technologies (Dosi, 1982; Mowery and Rosenberg, 1979). The debate gave rise to sociological and economic approaches, in which technological development was conceived of as an interaction process between societal, economic, political and technological factors, the

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influence of which could not easily be distinguished one from another (Bijker et al., 1987; Bijker and Law, 1992). Studying technological development increasingly became a historical undertaking. Many historians of technology, as well as historians in general, are 'splitters' in the sense that they seek to make very detailed accounts of history and believe that more general perspectives are impossible.[1] The unsettling aspect about this development in the academic field is that it easily gives rise to the belief that anything might happen, that regularities cannot be found. There is, however, a need to 'lump' brute facts in the history of technology together and to seek to find more general patterns. Evolutionary economics has developed a clear view on what influences the development of technology. In this contribution, we argue that such a theoretical approach is necessary, but that the theory proposed in evolutionary economics needs to be amended.

In the literature, the concepts of demand-pull and technology-push refer to either the sources of innovation, looking at the agent who innovates, or to the motivations for innovators (see Coombs et al., 1987; Mowery and Rosenberg, 1979; Rothwell, 1992; Schmookler, 1966). In this paper, we investigate the influence of changes in the state-of-the-art in technological knowledge, on the one hand, and demand factors, on the other hand, on the development of technological paradigms. Changes in state-of-the-art in technological knowledge materialize in marked improvements in existing products or in the creation of new ones. Actual or potential adopters of a technology at a specific moment in time, given a certain price vector, define demand. Demand factors point to the emergence or existence of a market for a product embodying technological knowledge.

We discuss here the emergence and development of paradigms in computing technology. Computing technology is believed to be the root cause of the present Kondrattieff wave, profoundly affecting today's economy (Freeman and Perez, 1988). Rapidly developing computing technology became an enabling force behind broader economic and social changes, for instance in management (Scott Morton, 1991), communication, media (De Sola Pool, 1990) and the financial sector (Colton and Kraemer, 1980; Michie, 1999; Nightingale and Pool, 2000). Many scholars take this field of technology as an example in more general discussions of the character of technological development. We realize that changes in technological knowledge or demand are not the only influences on the development of a technological paradigm (Achilladelis and Antonakis, 2001). Agents involved in innovation make their own decisions, but these decisions are affected by other factors as well. Public policy is one such factor that springs to mind in the context of computing technology. Another issue is the innovative culture in which a firm finds itself, for example in an area such as Silicon Valley where in more recent years much innovative activity is clustered (Saxenian, 1994). We focus on demand and technological knowledge, as these play the most important role in the long term, and, as such, facilitate comparisons between different fields of technology. Other authors, particularly in evolutionary economics, also consider technological knowledge and demand the

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[1] The distinction in the approach of historians between 'lumpers' and 'splitters' is from *the Economist* (September 5, 2000 "Big-picture history").

most important factors in explaining the development of technological paradigms (Adner and Levinthal, 2001; Dosi, 1988; Kim, 2003).

We demonstrate that periods and fields of technology exist in which either changes in technological knowledge development *or* changes in the market explain how the computing technology paradigm evolves. Moreover, and in contrast to what is generally claimed in the literature in evolutionary economics (which we survey in Sect. 2), we demonstrate that the *emergence* of new technological paradigms can also be enabled by demand factors (see also Tripsas, 2001), whereas developments in technological knowledge may also exert influence within the boundaries of a paradigm. Statements about the effects of changes in technological knowledge or demand on technological paradigms can be made only for specific periods and fields of technology (cf. Smith and Marx, 1994).

After discussing the literature in evolutionary economics on the concept of technological paradigms and the forces behind their dynamics, we elaborate on our methodology in Section 3. In Section 4 we discuss the history of computing. Discussion and conclusions ensue.

2 Evolutionary economics on the development of technology

The development of technological knowledge is often perceived to have an 'intrinsic dynamics' (Molino, 1999). Physical factors or physical nature can, of course, stimulate development in a specific direction and facilitate a higher speed of development (Vincenti, 1994). This was the case in solid-state physics, leading to drastic improvements in microelectronics. Physical factors can certainly also set boundaries for or hinder the development of technological knowledge by closing off specific paths of development, or by raising problems that limit the speed of development, thus explaining the limited advances in technology in specific periods. The effects of physical factors differ across fields and periods, a fact noted by evolutionary economists as well (Malerba and Orsenigo, 1997, p. 94; Dosi, 1988).

Freeman and Perez (1988) argue that changes in technological knowledge are the most important explanation for changes in what they call techno-economic paradigms. They hold that such paradigms affect broad sectors of the economy and society. They consider techno-economic paradigms central in the emergence of long waves in the economy, and argue that microelectronics and computers are central to the present wave. A techno-economic paradigm refers to a broader set of phenomenon than the concept of technological paradigm that we employ (cf. Dosi, 1982, 1988). A technological paradigm refers to the core knowledge base involved in a specific field of technology and to common aspects of the problem solving activities of engineers in that field (Dosi, 1982, 1988; Dosi et al., 1993). Development along the lines of the paradigm is called a technological trajectory.[2]

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[2] A 'technological paradigm' defines contextually the needs to be fulfilled, the scientific principles and the material technology to be used. In other words, a technological paradigm can be defined as a 'pattern for solution of selected techno-economic problems based on highly selected principles derived from the natural sciences. A technological paradigm is both a set of *exemplars* (...) and a set of *heuristics* ... ' '*A technological trajectory* (...) is the activity of technological progress along the economic and technological trade-offs defined by a paradigm'. Dosi (1988, p. 224, italics in original).

The original meaning of the concept of technological regime refers to the basic design features of a specific product and to the technological framework engineers in the field use explicitly or implicitly that shape their activities.[3]

In the field of evolutionary economics, scientific advances are believed to create new paradigms – the development of scientific or technological knowledge is considered to be the major if not the sole factor determining changes of paradigms or regimes. Demand is considered only to exert influence *within* the boundaries of paradigms. Demand selects between different paradigms and affects the trajectories of those selected. Dosi notes the following respecting 'changing demand conditions':

> '(. . .) these factors are likely to be fundamental ones, influencing both the rate and direction of technical progress, but *within the boundaries* defined by the nature of technological paradigms.' (Dosi, 1988, p.227)

> '(. . .) environment-related factors (such as demand, relative prices, etc.) are instrumental in shaping (a) the rates of technical progress; (b) the precise trajectory of advance, within the (limited) set allowed by any given 'paradigm'; and (c) the selection criteria amongst new potential technological paradigms. However, each body of knowledge, expertise, selected physical and chemical principles, etc. (that is, each paradigm) determines both the opportunities of technical progress and the boundaries within which 'inducement effects' can be exerted by the environment. Moreover, the source of entirely new paradigms is increasingly coming from fundamental advances in science and in the (related) 'general' technologies (e.g. electricity, information-processing, etc.).' (Dosi, 1988, p. 228)[4]

According to Dosi, his position can 'help resolve the long debate in the literature about the relative importance of 'demand pull' versus 'technology push' (Dosi, 1988, p. 228). In later publications, this view has not been qualified, let alone abandoned. In addition, the OECD (1992, p. 39) speak of a 'new technological paradigm emerging from the techno-scientific breeding ground'.

We share with evolutionary economics the attention to the influence of technological knowledge and demand on the development of technology. However, we put into question the sequence postulated in evolutionary economics concerning their influence during the different phases of development of a technological paradigm.

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[3] See Freeman (1997) and Freeman and Perez (1988). Compare Nelson and Winter (1982) who discuss technological regimes. The concept of technological regime has also been used in a broader sense, referring to the characteristics of innovation processes in specific industrial sectors (Malerba and Orsenigo, 1997), and to formal and informal rules sets underlying innovation processes in specific products (Rip and Kemp, 1998). See also: Georghiou et al. (1986), Kemp (1994), Nelson and Winter (1982) and Van den Ende and Kemp (1999).

[4] Dosi does remark that the speed of and way in which an innovation is generated depends on the specific sector and time involved. This would depend on the opportunities for innovation that each paradigm leaves (Dosi, 1988, p. 229).

3 Methodology

We apply counterfactual analysis to determine which of the two factors was most important in the development of computing technology during what period. Cowan and Foray (2002) have argued that counterfactual reasoning is in fact ubiquitous in science and that it fits particularly well with the historical character of evolutionary economics (see also Booth, 2003). In fact, this is an approach very much in line with Schumpeter's *Capitalism, Socialism and Democracy* (1943, especially chapter 17).

We actually follow Dosi in making counterfactual comparisons over time in a specific field of technology. For this purpose, we take the position of the adopter of a new product - normally a firm - at the time t when a product was adopted.[5] The adopted product can be completely new or an existing product that is markedly improved in terms of price-performance ratio. Performance may refer to 'basic' performance parameters, such as the speed and memory capacity of computers, or to often related performance characteristics actually evaluated by users, such as user friendliness. We raise the question: would the adopter also have accepted this product at time $t - 1$, for instance, a number of years earlier, if it had been offered then? If the answer is yes, the absence of supply of the product at time $t - 1$ (or, the price-performance ratio of the product at time $t - 1$) is the reason for its non-adoption at time $t - 1$, and thus the change in technology on offer is the main reason for its adoption at time t. If the answer is no, the question is whether the product as offered at time t (including its price-performance ratio) is or could have been offered at time $t - 1$, considering the state of technology at that time. If the product could have been offered, apparently the lack of demand is the reason that it was not adopted at time $t - 1$, and demand is the main reason for its adoption at time t. If this question is to be answered negatively, apparently both supply and demand changed in the period between $t - 1$ and t, and both have to be considered enablers of the adoption at time t.

We base our claims on the behavior of potential adopters with respect to a technology that was not actually offered on a study of their activities, their situation and the cost they faced with respect to other production factors. Particularly, the volume and type of their activities can indicate if the technology would have rendered advantage and thus if the user would have adopted it. To be able to show that the requirement Mowery and Rosenberg (1979, p. 141) propose that 'a shift in demand curve must be shown to have occurred' a very close look at the users from a specific era is needed – closer than, e.g., Aversi et al. (1999) employ. Techniques such as simulations can complement but not substitute for the close empirical enquiry entailed.

Our procedure is similar to the approach of Dosi (1988), who evaluates and tries to understand whether a technology would have been adopted in a previous era given the respective demand conditions ('relative prices'). In case a technology

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[5] Final consumers are different from firms which chose to acquire a product, even if it is the same product. Decision-making processes of firms are more rational, as for firms more time lapses between a decision and the actual behaviors. Still, the perceived rationality of decision-making processes in firms should not be overestimated. We do want to submit that the method used here is useful for consumer goods, as well.

would have been adopted under the conditions existing previously, he concludes that the new technology must be superior to the old ones:

> ‘[I]nnovation yields new techniques which are likely to be superior to the old ones irrespective of relative prices, either immediately, as often is the case of many microelectronics-based processes (...), or after a learning period (...). If the new techniques had existed before they would also have been adopted at the ‘old’ relative prices.’ (Dosi, 1988, p. 227)

Under these circumstances, developments in technological knowledge have (primarily) shaped a paradigm. Our counterfactual reasoning entails that we extend our definition of demand to latent demand: the demand at time $t-1$ should the product have been offered. Others find that latent demand is of great importance to understand the development of technology, too (Tidd et al., 2001, p. 164). The procedure we adopt is similar to the approach in so-called ‘technology measurement’-studies of the 1980s (Alexander and Mitchell, 1985; Saviotti, 1985; Saviotti et al., 1982). The objective there was to determine the rate of progress made in specific fields of technology, measured by means of certain performance characteristics. These authors and others based their estimates on the prices and performance of the supply, not on data on the actual users. In contrast to the technology measurement approach, we study historical changes in the situation of users instead of estimates of users’ preferences based on product prices.

4 Computing technology

How does the literature on the history of computing technology address the role of knowledge and demand? Until well into the 1980s, an internalist view of the development of computing technology prevailed in the literature, focusing on inventions and the people that made them. Most authors mainly explained the growth of the field with reference to developments in the relevant knowledge base (Goldstine, 1972; Williams, 1985). The role of the military in the development of early computers was the only demand factor considered (Goldstine, 1972; Mahoney, 1988; Metropolis et al., 1980; Nijholt and van den Ende, 1994; Williams, 1985). Given the complexity of developments in the field of computing technology presented in Figure 1, where especially in the early phases many sub-paradigms can be distinguished (including digital, electrical devices but also mechanical and electronic ones), such a view seems evidently overly simplistic. Beniger (1986) stresses one element in the context in which computing technology developed, a general control crisis emerging in the nineteenth century in Western societies, and continuing into the 20^{th} century. The growing speed and complexity of the material processing systems (encompassing production, distribution and sales systems) caused the control crisis. In Beniger’s analysis, these societal changes were the background of changes in demand for computing technology. Beniger, however, takes a social determinist stance, disregarding the development of technological knowledge (cf. also Campbell-Kelly and Aspray, 1996; Ceruzzi, 1998). On the history of computing technology, scholars either dedicate attention to knowledge development – with

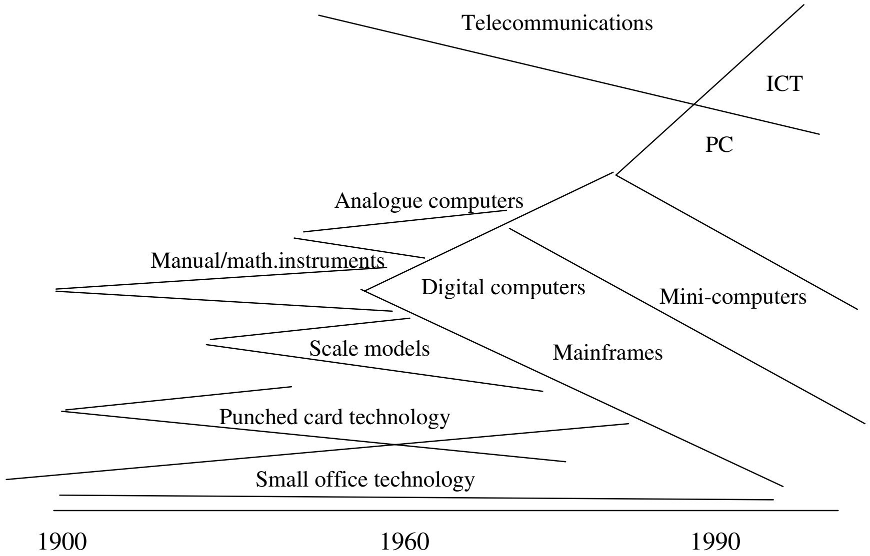

Fig. 1. Paradigms in computing technology. The slopes of the lines indicate the growth of the market for each technology. Source: Van den Ende and Kemp (1999)

possibly a minor role for demand from the military – or to societal forces. No one presents a coherent perspective incorporating the different forces at work to explain the development of the paradigms in the field of computing technology.

This paper demonstrates that technological knowledge and demand are both important, albeit that their importance fluctuates across time. Demand factors were paramount in the development of computing technology in the period before 1960, with knowledge factors dominating thereafter. A different kind of knowledge development was at work for the period between 1960 and 1990 than was the case for the period after 1990. We discuss the three periods (1900–1960, 1960–1990 and 1990 to the present) in turn. For the first period, 1900–1960, we discuss cases of users of computing technologies more in depth, based on primary sources. As the 1900–1960 period is less well known, and as this period constitutes the most important challenge to the theory in evolutionary economics as to the way in which technological paradigms develop, we discuss it at some greater length. The treatment of the other two periods is based more on secondary sources.

Growing demand (1900–1960)

In the period 1900–1960, the field of computing technology included three different types of activities: data processing, technical and scientific computing, and computing for process control, mainly in industry. Different people performed these activities for different purposes, and they applied different computing technologies. Technologies applied in the field of data processing were desk calculating machines and punch card machines. Engineers and scientists applied slide rules, graphical aids and analog computing machines for technical and scientific computing activities. Electrical and mechanical control devices (supported by servomechanisms) were used for process control. Occasionally, technologies from one field were applied in another, such as punch card machines that were used for technical scientific computations by some specialized computing bureaus in the US and UK (Campbell-Kelly and Aspray, 1996; Ceruzzi, 1997, 1998).

Engineers and scientists developed the first electronic digital computers during and shortly after the Second World War (Campbell-Kelly and Aspray, 1996; Williams, 1985). During the 1950s, the digital computer started to unite the three fields. Scientists, engineers and manufacturing firms developed and introduced many new computing technologies, such as desk calculators, punch card machines, various types of scale models and analog computers (see Fig. 1 and Campbell-Kelly and Aspray, 1996, and Nijholt and Van den Ende 1994). Several of them were applied in industrial and university research laboratories, which were newly established in this period, performing a range of computational tasks (Reich 1985; Wildes and Lindgren, 1985). Government agencies and firms also applied computing technologies, such as the punch card machine, for their administrative tasks (Yates, 1989). In industry computing devices were used for automatic control, which became an issue especially in the period around the Second World War (Bennett, 1991). Different computing technologies were notably applied separately by the same organization.

We discuss two cases of specific large-scale applications of computing technology by different users, both from the Netherlands, to investigate the development of demand in this period: tidal calculations and statistical data processing. These cases are representative for other uses of computing technology in this era in other countries as well; indeed, the relative scale and certainly the scope of the kind of uses that computing technology could be put to might have been larger in the Netherlands than elsewhere.

Tidal calculations

In the Netherlands, tidal calculations are used to predict changes in the tidal pattern and water levels during storms, as part of a preparation for hydraulic works that serve to reclaim land from the sea and to protect the land against floods (Disco and Van den Ende, 2003; Van den Ende, 1992, 1994b). These works involved the enclosure of the Zuiderzee (now IJsselmeer) by a 30 kilometer dam between 1918 and 1932, and the so-called Delta Works, carried out between the mid 1950s and 1986. In the second half of the nineteenth century, civil engineers applied intuitive methods to predict the effects of hydraulic works on tidal patterns and the propagation of storm surges, and made simple computational estimates. Between 1900 and 1960, engineers and scientists developed four new methods for these computations: manual computational methods (1918), electrical analog computing methods (1945), large hydraulic models (1948), and the digital computer (1956).

The Zuiderzee works were the first for which the old intuitive computational methods were considered to lack the required accuracy. Civil engineers, local and regional authorities, and members of parliament demanded better computations. A team of engineers, led by the then famous physicist and Nobel Laureate Lorentz, worked for eight years to produce exact calculations to predict the changes in water movements after the dam had been completed, spending numerous months on manual computing work alone. Their predictions were very close to the actual increases in tidal movements; in modern hydraulics, this is still revered. This method of manual computing was practiced on a much larger scale in the 1930s, when a standing team of engineers of substantial size was created just to perform such calculations for the Delta works in the southwest of the Netherlands, the estuary of the rivers Rhine, Meusse and Schelde. In 1953, this region was flooded, killing many and destroying property. Experiments started in the mid-1940s, resulted in the construction of two large analog computers devoted to this problem in the 1950s and 1960s. Furthermore, large scale-models were constructed for the same purpose towards the end of the 1940s. In 1956, for the first time, a digital computer was applied.

This case demonstrates that the size of computing activities for the planning of hydraulic works increased considerably in the course of time. There was significant and increasing pressure, such as from politicians and municipalities, to get accurate estimates about the consequences of projected hydraulic plans on water levels and currents. An ever-greater number of alternatives had to be evaluated with an ever-greater precision, so that each party could get insight into the consequences of projected works. The scientists involved developed or applied several new computing technologies as they dealt with the increasing complexity of the hydraulic works, covering large and geometrically complex areas. This complexity is a demand factor since it was mainly instigated by broader societal developments. The fact that civil engineers started developing new computing technology, an unfamiliar field for them, underscores the importance of demand for the development of computing technology.

Advances in the knowledge of computing technologies were of minor influence on the increasing use. Scale models, for instance, were already available, but were not applied because they were still considered too expensive. Lorentz explicitly rejected the idea of building a scale model for the Zuiderzee works (Staatscommissie, 1926). Analog computing technologies were available for some decades, for instance, in some harbors (Liverpool, Hamburg) mechanical tide predictors were applied for just predicting the unchanged tidal pattern (not to predict the effects of changes in the pattern as a consequence of hydraulic works) (Van den Ende and Nijholt, 1994). The analog machines developed for the Dutch situation had important new elements, but did not provide major improvements in terms of price-performance ratio compared to prior technologies. We may conclude that scale models and analog computing technologies could have been offered earlier, considering the state of the art at that time. So, as we have indicated in Section 3, the lack of demand has to be considered the main reason for their actual later adoption. New computing technology did facilitate the evaluation of and discussions about hydraulic plans, but if it had not been available, the evaluations could have been executed manually as before. This also appears from the fact that manual computing remained in use well into the 1950s. The conclusion should then be that new technologies would not have been applied much earlier if they had been available, and that the application of these technologies depended on the growing demand for computing aids.

Statistical data processing

The same pattern can be found in the field of government statistics (Van den Ende, 1994a,b). Between 1900 and 1960, Statistics Netherlands (CBS) applied an increasing number of desk calculating machines and punch card machines for its operations. In the beginning of the century, CBS performed all necessary computations manually. For large assignments, large numbers of temporary workers were hired. In 1916, during reorganization, it acquired punch card machines for the department that compiled trade statistics. Only in the 1930s did the number of such machines in use start to grow. Around 1950, the Bureau counted about 60 machines processing punched cards, operated by about 200 employees, processing millions of punched cards each year. In 1960, Statistics Netherlands introduced the digital computer, a particularly expensive device at that time.

The statistical office responded to the growing demand from government agencies and others for statistics. It compiled a growing number of statistics in the course of the century, while the accuracy required and the quantity of available primary data grew. The much more active economic policy of the Dutch government that started before and continued after the Second World War was an important stimulus for the extension of statistical activities. Especially from the late 1950s onward, economic and social policy were actively trying to influence society and the economy with the construction of the welfare state (Van Zanden, 1996). These developments created a growing demand for new computing technology.

Developments in computing technology can hardly explain the growing degree of application of computing technologies. Price-performance improvements of punch card and digital computing technology were minor. For instance, in 1925 in the Netherlands, a tabulating machine cost *ƒ*2100 per year to rent, approximately equivalent to one-and-a-half years' salary for a machine operator. In 1957, the rent of the machine had risen to $20,000 per year, four years salary (Van den Ende, 1994b, pp. 173–174). Productivity improvements seem only to have been slightly higher. Limited improvement of computing technology in terms of price-performance stemmed from the fact that computing technology was based on mechanical and electrical knowledge that already existed at the end of the nineteenth and the beginning of the twentieth century. No fundamental new knowledge was applied or developed. The punch card technology from the 1950s most probably would not have been applied by the Bureau in 1930 if it had been available, because the smaller workload, the smaller number of tables required, and the lower accuracy requirements of the data processing operations would not have justified its application. So, in line with our methodology introduced in Section 3, we have to conclude that demand has to be considered the most dominant explanation for the adoption of the faster punch card technology in the 1950s.

This even applies to the first digital computer in 1960. Compared to punch card machines, the digital computer could perform more calculations and could integrate a number of operations in a single program. However, digital computers were very expensive compared to other technologies, and prone to failures. The adoption of the digital computer in 1960 by the CBS also needs to be explained by the ever-growing quantity of statistical work to be performed and not by the new possibilities on offer. The reason that digital computers did not provide a major improvement for the user compared to prior technologies has to do with the technological knowledge embodied in them. The most important developments concerned the composition of different components; components that had already been developed and applied in computing technology. In 1962, J. Mauchly and J.P. Eckert, who build the famous ENIAC, which is often considered the first electronic computer, commented that most of the knowledge that they used had already been available ten to fifteen years before (Nijholt and Van den Ende, 1994, p. 153). The fact that the first digital computers did not offer a major improvement for users also explains the slow diffusion of this technology in its first decade, in the 1950s.

Diffusion of digital computers, 1960–1990

The second period, from 1960 to 1990, is a period of the impressive diffusion of electronic digital computers. Throughout this period, digital computing technology significantly improved on many performance characteristics, such as speed, memory capacity, size and reliability, while at the same time its relative price decreased drastically. The manufacturers of computers, moreover, used part of the speed and memory performance of computers to improve the user friendliness of the software. This process started in 1960, when manufacturers brought transistorized, second generation, digital computers onto the market (Ceruzzi, 1998, pp. 65–77). It continued for decades, as chip technology – initially memory chips, and later on the microprocessor – appeared on the market, leading to third-generations computers. Transistors and chip technology were essential for the introduction of new types of computers, particularly minicomputers and personal computers (Langlois, 1992). Regression analysis demonstrates that the price-performance ratio of different types of computers improved by a factor of about 20% a year between 1951 and 1984, taking speed and memory capacity as main indicators of performance (Gordon, 1989).[6] After 1984, the process of sustained improvement in price-performance measures continued. The extent and duration of these price-performance improvements may well be unprecedented in the history of technology, since no examples can be found in the literature that equal this technological development (Alexander and Mitchell, 1985; Knight, 1985; Saviotti, 1985; Saviotti et al., 1982).

It is clear that the development of fundamental technological knowledge, particularly in the field of solid-state physics and microelectronics, were important in the development of the digital computer in this period. The development of scientific and technological knowledge was highly rewarding as a resource for improvement

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[6] Although the price of first generation digital computers already started to decrease in the late 1950s, we take the first practical application of second-generation computers around 1960 as a starting point for the period where development of computing technology was knowledge-enabled. New product knowledge, and particularly knowledge in the field of micro-electronics, caused price-performance ratios to increase for second-generation machines, whereas the improvements of first generation computers in the 1950s were mainly due to 'traditional' learning effects.

of products such as chips and computers. Although traditional learning effects, such as better organization of design and production and improved distribution channels, have certainly added to the improved price-performance ratio of the digital computer, the development of fundamental technological knowledge stands out. The trajectory started by solid-state physics provided physicists and engineers enormous possibilities for advancing computing technology (Braun and MacDonald, 1978; Queisser, 1988). The improved and cheaper second-generation digital computers found applications, particularly in data processing, that would not have justified the application of the more expensive and lower performing first generation computers. This certainly applied to the minicomputers and third generation computers, introduced in the 1960s (Ceruzzi, 1998, pp. 182–191). Had digital computers with these prices and performance been available before, they would have undoubtedly been used earlier, even before the 1950s. So, in line with our methodology, we have to consider the change in computing technology in this period as the dominant factor in its adoption.

Compared with previous times, developments in technology and technological knowledge now resulted in far greater societal impacts. The availability of improved and cheaper computing technology, based on microelectronics, formed an important impetus for organizations to computerize all kinds of data processing and computing activities, including the development of computer-based management information systems. The scope and scale of the activities of organizations were often changed in turn (Venkatraman, 1991). The sheer number of computer applications increased far more rapidly than in previous periods. In many applications, the digital computer substituted other computing technologies, but many new applications emerged as well.

The development of technological knowledge enabled development in computing technology paradigms. Had the new technology, with its price-performance ratio, been available earlier, it would also have been adopted earlier (for instance for tidal calculations and statistical data processing). Technological knowledge, particularly knowledge of microelectronics, led to the improvement of existing mainframe computers, but also to the emergence of new products, particularly mini-computers and personal computers.

Connectivity, 1990–the present

After 1990, the convergence of two types of technology, computing and telecommunications technology, was central. In a short period of time, the use of computers for communication purposes, particularly by means of email and Internet, became popular. Most explanations for this development point to the availability of Internet technology for a larger public due to the end of the cold war, and the increasing overall demand for communication (Abbate, 1999). Such an explanation underestimates the influence of development of technological knowledge enabling the convergence of the two types of technologies. The end of the cold war did allow for what Levinthal (1998) calls 'speciation' – the introduction of existing technological knowledge in a new environment where it can be put to good use and where resources are available more abundantly. The increasing digitization of telecommunications technology and rapid development of knowledge of the physical connectivity of telecommunication and computer technology were preconditions for the convergence of the two kinds of technologies. Several types of new knowledge were developed for this purpose already at the end of the 1960s and in the 1970s, such as packet switching, layering and routing (Abbate, 1999, pp. 56–64 and 114–130; Moschovitis et al., 1999), and browsers and the World Wide Web (Abbate, 1999, pp. 212–216). These types of knowledge were required for the connectivity of computing technology and communications technologies, and for the rise of the Internet.

Another factor is needed to explain the rapid adoption and diffusion in the 1990s of Internet technology, the local area networks that many organizations established. These were often not primarily meant for external communication purposes, but instead had to facilitate the implementation of new versions of user software within the organization. Now, new software programs could be installed once on the local server, instead of on each individual desktop computer in the organization. These local area networks generated scale effects in the maintenance of internal computer infrastructures of organizations and their communication systems. Local area networks were an essential precondition for the subsequent success of Internet and other computer-based communication systems.

While the post 1990 era does not offer a clear story of developments in technological knowledge, being the only enabler of developments in computing technology, it is clear that rising demand cannot explain the convergence of computing and communication technologies. If the new technologies would have been offered before, it is most likely that they would have been adopted then. The demand for computer supported communication that became manifest in the post 1990 period already existed. Therefore, in line with our methodology introduced in Section 3, technological factors, developments in the knowledge about connecting computing and telecommunications technologies, specified above, and the complementary use of an existing infrastructure, were important for the development of computing technology. These factors made possible the computer's new and warmly welcomed communication applications. Although for this third period, as well as for the second period, developments in technological knowledge are the enablers, and so the nature of the technological knowledge involved was different. Before 1990, advances in microelectronics, leading to improved price-performance ratios of stand-alone computers, were the most important enablers. After 1990, it becomes increasingly difficult to make overall measurements of these ratios, since new types of computers (notebooks, PDAs) were introduced. According to some, for instance Jorgenson and Stiroh (2000, p. 127), the price-performance indicators still improved markedly as compared to the period between 1960 and 1990, from 20% up to 28% between 1995 and 1998. Others indicate that prices of computing technology stabilized at the end of the 1990s (CBS, 2002).

5 Discussion and conclusion

The discussion on the influence of demand-pull and technology-push on the development of technological paradigms has at times been a confused one. In this paper, we defined the concepts of technology-push and demand-pull more specifically, referring to developments in technological knowledge and market changes, both of which are important in determining the course a technological paradigm takes. For computing technology, we demonstrated that, during different periods of time, the influence on the development of the paradigm of computing technology of each of these factors fluctuated.

Computing technology developed in three different phases. In the *first* phase, between 1900 and 1960, demand-pull was the significant factor. The basic technological knowledge had already been available for quite some time. In some cases also the computing devices were available, while in other cases, they could have been developed with limited additional innovative activities, had the (potential) demand not been lacking. We have shown that this notably also holds for the digital computer. Demand for computing capacity from the military and from other users grew to some degree in the 1940s and 1950s, creating the main precondition for the initial adoption of the digital computer. However, even in 1948, depressed expectations of demand for computers were purportedly expressed.[7] These views did underestimate demand, especially in the very long term, but actually make clear that the growth of demand was initially only gradual.

In the *second* period, between 1960 and 1990, knowledge development in the field of microelectronics played the most important role. Although some authors interpret the increasing diffusion in this period as demand growth (Friedman, 1989), the counterfactual method adopted here indicates that autonomous growth of demand, independent of the supply, was not the main force. After 1990, during the *third* period, the development of technological knowledge leading to the convergence of computing and telecommunications technology needs to be addressed. In both of the latter periods, the advances of knowledge facilitated strongly improved price-performance ratios of computers and the introduction of new computing technologies. The development of knowledge in these periods also allowed for computing technology to have a significant effect on society and the economy at large.

The upshot of our analysis, and the relevance for the evolutionary economics literature, is that advances in scientific and technological knowledge are not always the main instigator of new technological paradigms. Paradigms may also find their origin in demand conditions. Moreover, the further course of development of a technological paradigm can be determined by both technological developments and by demand. We share with evolutionary economics the attention for the influence of technological knowledge and demand on the development of technology. However,

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[7] Historians of technology have not been able to verify the authenticity of the often-cited expectation of Thomas J. Watson Sr., former CEO of IBM, however, that there would be a world market for only five computers (Campbell-Kelly and Aspray, 1996, p.105). People directly involved in the design of computers estimated a very low demand for computers in the 1940s (Van den Ende and Kemp, 1999, pp. 845–846).

we put into question the sequence postulated in evolutionary economics concerning their influence during the different phases of development of a technological paradigm.[8]

References

Abbate J (1999) Inventing the internet. MIT Press, Cambridge, MA

Achilladelis B, Antonakis N (2001) The dynamics of technological innovation: the case of the pharmaceutical industry. Research Policy 30: 535–588

Adner R, Levinthal D (2001) Demand heterogeneity and technology evolution. Implications for product and process innovation. Management Science 47(5): 611–628

Alexander AJ, Mitchell BM (1985) Measuring technological change of heterogeneous products. Technological Forecasting and Social Change 27(2/3): 161–195

Arthur B (1988) Competing technologies: an overview. In: Dosi et al. (eds) Technical change and economic theory, pp 590–607. Pinter, London

Aversi R, Dosi G, Fagiolo G, Meacci M, Olivetti C (1999) Demand dynamics with socially evolving preferences. Industrial and Corporate Change 8(2): 353–408

Ayres RU (1985) A Schumpeterian model of technological substitution. Technological Forecasting and Social Change 27: 375–383

Beniger JR (1986) The control revolution. Technological and economic origins of the information society. Harvard University Press, Cambridge, MA

Bennett S (1991) The industrial instrument – master of industry, servant of management. Automatic control in the process industries, 1900–1940. Technology and Culture 32: 69–81

Bijker WE, Hughes ThP, Pinch TJ (eds) (1987) The social construction of technological systems. MIT Press, Cambridge, MA

Bijker WE, Law J (eds) (1992) Shaping technology, building society. MIT Press, Cambridge, MA

Braun E, MacDonald S (1978) Revolution in miniature. The history and impact of semiconductor electronics. Cambridge University Press, Cambridge

Booth C (2003) Does history matter in strategy? The possibilities and problems of counterfactual analysis. Management Decision 41(1): 96–104

Campbell-Kelly M, Aspray W (1996) Computer. A history of the information machine. BasicBooks, New York

CBS (2002) Producentenprijzen naar ProdCom, vanaf 1995 (ProdCom Producer prices since 1995). Dutch Central Bureau of Statistics, Voorburg/Heerlen

Ceruzzi PE (1997) Crossing the divide: architectural issues and the emergence of the stored program computer, 1935–1955. IEEE Annals of the History of Computing 19(1): 5–12

Ceruzzi PE (1998) A history of modern computing. MIT Press, Cambridge, MA

Colton KW, Kraemer KL (1980) Computers and banking. Electronic funds transfer systems and public policy. Plenum Press, New York

Coombs R, Saviotti P, Walsh V (1987) Economics and technological change. MacMillan, Houndmills

Cowan R, Foray D (2002) Evolutionary economics and the counterfactual threat: on the nature and role of counterfactual history as an empirical tool in economics. Journal of Evolutionary Economics 12(5): 539–562

De Sola Pool I (1990) Technologies without boundaries. On telecommunications in a global age. Harvard University Press, Cambridge, MA

Disco N, Van den Ende J (2003) Strong, invincible arguments? Tidal models as management instruments in Twentieth-century Dutch coastal engineering. Technology and Culture 44(3): 502–535

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[8] There is another way in which the case of computing technology is relevant for theorists. Arthur (1988) and Sahal (1981) have argued that, after the introduction of a completely new product, only learning effects generate price-performance improvements and fundamental advances in technological knowledge play a minor role. In the case of digital computers, fundamental advances in technological knowledge caused profound and sustained improvements in the price-performance ratios after the product had been introduced. One other example would be renewable technologies (notably windmills).

Dosi G (1982) Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change. Research Policy 11: 147–162

Dosi G (1988) The nature of the innovative process. In: Dosi G et al. (eds) Technical change and economic theory, pp 221–235. Pinter, London

Dosi G, Freeman Ch, Nelson R, Silverberg G, Soete L (eds) (1988) Technical change and economic theory. Pinter, London

Dosi G, Malerba F, Orsenigo L (1993) Evolutionary regimes and industrial dynamics. In: Magnusson L (ed) Evolutionary and Neo-Schumpeterian approaches to economics. Kluwer, Boston

Freeman Ch (1997) The political economy of the long wave. In: Tylecote A, van Straaten J (eds) Environment, technology and economic growth. Cheltenham, Elgar

Freeman Ch, Perez C (1988) Structural crises of adjustment, business cycles and investment behavior. In: Dosi G et al. (eds) Technical change and economic theory, pp 38–66. Pinter, London

Friedman AL (1989) Computer systems development. History, organization and implementation. Wiley, Chichester

Georghiou L, Metcalfe JS, Gibbons M, Ray T, Evans J (1986) Post-innovation performance: technological development and competition. MacMillan, London

Goldstine HH (1972) The computer from Pascal to Von Neumann. Princeton University Press, Princeton

Gordon RJ (1989) The postwar evolution of computer prices. In: Jorgenson DW, Landau R (eds) Technology and capital formation, pp 77–125. MIT Press, Cambridge, MA

Jorgenson DW, Stiroh KJ (2000) Raising the speed limit. U.S. economic growth in the information age. Brookings Papers on Economic Activity 1: 125–235

Kemp R (1994) Technology and the transition to environmental sustainability. The problem of technological regime shifts. Futures 26(10): 1023–1046

Kim WJ (2003) Measuring the role of technology-push and demand-pull in the technological innovation of semiconductors industry. The case of the global DRAM market. Working Paper, Yale School of Management

Knight KE (1985) A functional and structural measurement of technology Technological Forecasting and Social Change 27(2/3): 107–127

Langlois RN (1992) External economies and economic progress. The case of the microcomputer industry. Business History Review 66(1): 1–50

Levinthal DA (1998) The slow pace of rapid technological change. Gradualism and punctuation in technological change. Industrial and Corporate Change 7(2): 217–247

Mahoney MS (1988) The history of computing in the history of technology. Annals of the History of Computing 10(2): 113–125

Malerba F, Orsenigo L (1997) Technological regimes and sectoral patterns of innovative activities. Industrial and Corporate Change 6(1): 83–117

Metropolis N, Howlett, J, Rota G-C (eds) (1980) A history of computing in the Twentieth Century. Academic Press, New York

Michie RC (1999) The London stock exchange. A history. Oxford University Press, New York

Molino AH (1999) Understanding the role of the technical in the build-up of sociotechnical constituencies. Technovation 19: 1–29

Moschovitis ChJP, Poole H, Schuyler T, Senft ThM (1999) History of the internet. ABC-Clio, Santa Barbara, CA

Mowery D, Rosenberg N (1979) The influence of market demand upon innovation: a critical review of some recent empirical studies. Research Policy 8: 103–153

Nelson RR, Winter SG (1982) An evolutionary theory of economic change. Belknap, Harvard University Press, Cambridge, MA

Nightingale P, Poll R (2000) Innovation in investment banking: the dynamics of control systems within the Chandlerian Firm. Industrial and Corporate Change 9(1): 113–141

Nijholt A, Van den Ende J (1994) Geschiedenis van de rekenkunst. Van kerfstok tot computer. Academic Service, Schoonhoven

OECD (1992) Technology and the economy. The key relationships. OECD, Paris

Queisser H (1988) The conquest of the microchip. Harvard University Press, Cambridge, MA

Reich LS (1985) The making of American industrial research. Science and business at GE and Bell, 1876–1926. Cambridge University Press, Cambridge

Rip A, Kemp R (1998) Technological change. In: Rayner S, Malone L (eds) Human choice and climate change, vol. 2. Resources and technology, pp 327–400. Batelle Press, Washington, DC

Rothwell R (1992) Successful industrial innovation: Critical success factors for the 1990s. R and D Management 22(3): 221–239

Sahal D (1981) Patterns of technological innovation. Addison Wesley, Reading, MA

Saviotti PP (1985) An approach to the measurement of technology based on the hedonic price method and related methods. Technological Forecasting and Social Change 27: 309–334

Saviotti PP, Stubbs PC, Coombs RW, Gibbons M (1982) An approach to the construction of indexes of technological change and of technological Sophistication: the case of agricultural tractors. Technological Forecasting and Social Change 21: 133–148

Saxenian A (1994) Regional advantage. Harvard University Press, Cambridge, MA

Schmookler J (1966) Invention and economic growth. Harvard University Press, Cambridge, MA

Schumpeter JA (1952 [1943]) Capitalism, socialism, and democracy. George Allen and Unwin, London

Scott Morton MS (ed) (1991) The corporation of the 1990s. Information technology and organizational transformation. Oxford University Press, New York

Smith MR, Marx L (eds) (1994) Does technology drive history? MIT Press, Cambridge, MA

Staatscommissie Zuiderzee (1926) Verslag van de Staatscommissie Zuiderzee. Landsdrukkerij, 's-Gravenhage

Tidd J, Bessant J, Pavitt K (2001) Managing innovation. Integrating technological, market and organizational change, 2nd edn. Wiley, Chichester

Tripsas M (2001) Understanding the timing of technological transitions: the role of user preferences. Working paper, Harvard Business School

Van den Ende J (1992) Tidal calculations in The Netherlands, 1920–1960. IEEE Annals of the History of Computing 14(3): 23–33

Van den Ende J (1994a) The number factory: punchedcard machines at the Dutch Central Bureau of Statistics. IEEE Annals of the History of Computing 16(3): 15–24

Van den Ende J (1994b) The turn of the tide. Computerization in Dutch Society, 1900–1965. Delft University Press, Delft

Van den Ende J, Kemp R (1999) Technological transformations in history: how the computer regime grew out of existing computing regimes. Research Policy 28: 833–851

Van Zanden JL (ed) (1996) The economic development of the Netherlands since 1870. Elgar, Cheltenham

Venkatraman N (1991) IT-induced business reconfiguration. In: Scott Morton MS (ed) The corporation of the 1990s. Information technology and organizational transformation, pp 122–157. Oxford UP, New York

Vincenti WG (1994) The retractable airplane landing gear. Technology and Culture 35: 1–33

Wildes KL, Lindgren NA (1985) A century of electrical engineering and computer science at MIT, 1882–1982. MIT Press, Cambridge, MA

Williams MR (1985) A history of computing technology. Prentice Hall, Englewood Cliffs

Yates J (1989) Control through communication. The rise of system in American management. Johns Hopkins, Baltimore London