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European competitiveness in information technology and long-term scientific performance

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The reasons behind the poor competitiveness of the European information technology (IT) industry *vis-à-vis* the US one have been discussed many times. This paper suggests that the long-term competitiveness of science-based industries is dependent on the ability of the underlying scientific base to support fast growing, turbulent and proliferating search regimes. This requires institutional mechanisms that foster severe selection of scholars from a large base, student and researcher mobility, and strong institutional complementarity with user industries. The paper compares the history of IT in the USA, Germany, the UK and France. Based on the analysis of the curriculum vitae of the top 1,000 scientists in computer science, it shows that these conditions were only met in the US academic system.

THAT EUROPEAN INDUSTRY IS NOT globally competitive in IT is well known, and has been the subject of many analyses and policy reflections at government and European Commission level. This assessment is based on converging data on some innovation inputs (R&D expenditure of firms), intermediate outputs (patents) and final outputs (international trade), although on different time scales.

In recent years, the European Commission has provided highly informative company-level analyses of R&D investment, with data related to 2004 (European Commission, 2005) and to 2009 (European Commission, 2010). In the two categories of IT hardware and software, there were a few European companies that spent more than €1 billion on R&D in the year 2004. In the IT hardware category, just four companies, from Finland (Nokia), Sweden (Ericcson), France (Alcatel) and Germany (Infineon Technologies) are recorded against six in the USA (Intel, HP, Cisco, Motorola, Texas Instruments and Sun) and four in Japan (Hitachi, Toshiba, NEC and Fujitsu).[1] The situation is even worse in software and computer services. SAP was the only European company spending more than €1 billion for R&D, while Microsoft, IBM and Oracle combined spent ten times that amount. In addition, there were 26 companies from the USA and three from Japan spending more than €100 million, against only six in Europe. The *2010 Scoreboard* (European Commission, 2010) has a different sectoral classification, but confirms the overall picture. In the semiconductors sector, within the top 20 R&D investors we find four European companies (STMicroelectronics, NXP, Infineon Technologies and ASML) against 10 from USA, two from Japan and four from Asia and other countries. In the software sector there are 14 US companies and six from Europe (SAP, UBIsoft Entertainment, Dassault Systemes, Sage, Amdocs and Invensys). There are few European companies who are not only in the top list of software producers, but also in the wave of internet-related innovators, or in the small group of successful startups, such as Google, e-Bay or Amazon, surviving the new economy bubble, or in the top list of companies offering IT-related services on a global scale. On a longer historical scale, companies which used to be national

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champions, such as Bull in France, Olivetti in Italy, Siemens Nixdorf in Germany, or ICL in the UK, are now virtually out of the market (Campbell-Kelly, 2003).

Second, data on patents may be criticized as less relevant for some subsectors of IT, such as software, but are clearly a crucial indicator for hardware-related sectors. The *Key Figures 2007* Report, using data from the European Patent Office, stated that:

> …the US is ahead of the EU in four out of six high-tech areas: (1) computers and automated business equipment, (2) micro-organisms and genetic engineering, (3) lasers, and (4) semiconductors. On the other hand, EU leads in aviation and in communication technology. (European Commission, 2007: 54)

Looking at patent data, it appears that in the patent class computer and automated business equipment the share of the EU-27 (the current 27 members of the EU) increases from 20.2% in 1995 to 25.8% in 2003, while in the same period the share of the USA declines from 50.3% to 43.5%. While the gap shrinks, it is still very large. Extending the analysis to 2005 on data from the Patent Cooperation Treaty (PCT), and using the larger definition of information and communication technologies (ICT), the *Key Figures 2008–2009* Report showed that the share of EU-27 of the world ICT patent applications decreases from 31.0% in 2000 to 24.8% in 2005 (European Commission, 2008: 68). The general comment was that:

> EU-27 is less specialised in high technology fields such as 'pharmaceuticals', 'computers, office machinery', 'telecommunications' and 'electronics' than in medium technology fields such as 'general machinery', 'machine tools', 'metal products' and 'transport. (European Commission, 2008: 69)

Over a longer period, Dalum *et al*. (1999) constructed the revealed technological advantage (RTA) indicator, as the share of a patent class in a country's overall patenting divided by the share of this patent class in total US patenting. Values below one indicate negative specialization. On the basis of US patents in the period 1969–1994, they showed that the RTA of Europe in ICT steadily decreased *vis-à-vis* competitors, from 0.86 in 1969–1974 to 0.84 in 1979–1984 to 0.73 in 1989–1994.

Furthermore, Dalum *et al*. (1999) calculated the long-run market shares in international trade for core ICT hardware, including computers and peripherals, semiconductors, and telecommunications equipment. Europe declined from 63% in 1961 to 41% in 1994, while in the same period Japan rose from 4% to 30% and the USA defended its share, from 27% to 25%.

Thus different indicators, although with different time scales, converge on supporting a broad picture of a competitiveness gap. Two qualifications are needed, however, which will be important for our interpretation.

First, European competitiveness is much stronger in telecommunications, where Nokia dominates several segments of the market and Ericcson is a large player (Santangelo, 1998; Hultén and Molleryd, 2003; Cantwell and Santangelo, 2003). In this paper we focus our attention on the narrow definition of IT (excluding communication technology), since explaining the causes of differential performances of Europe in the two broad areas of ICT would deserve a dedicated effort.

Second, while there are few European global players in IT, several companies are strong in niches of the market (Casper *et al*., 1999). As the *2010 Scoreboard* notes:

> The EU has some excellent software companies with strong positions in their subsectors or niches – there are just too few compared to the US. Examples include SAP in enterprise software, Autonomy in unstructured search and Sage in accounting and customer relationship management software for smaller businesses. (European Commission, 2010: 37)

In addition, Europe is relatively strong in embedded software, particularly in real-time applications for industrial automation, thanks to its leadership in the fields of mechanical and electrical engineering. However, this software is not typically sold separately from the equipment. Again, the reasons behind large differences in performance between large markets and niches are worth exploring.

Linking several European gaps: ICT competitiveness, productivity and growth

The weak competitiveness of the European IT industry is considered worrisome for several reasons, which extend far beyond the industrial policy domain. In fact, it has been shown that there is a relationship between these technologies, the slowdown in productivity in the European economy since the mid-1990s and the opening of a wide productivity gap with the USA since then. In turn, the productivity gap is considered to be the main source of the gap in rates of growth between the two economies. It should be noted that the wider definition of ICT is usually adopted in this literature.

Initial contributions pointed to the larger size of the ICT sector in the US industry and the earlier adoption of ICT in the US manufacturing industry as the main factors (Jorgenson and Stiroh, 2000). Subsequent analyses, based on sector-level data, showed that a large part of the gap is due to large gains in productivity in the US market service sector, which is a heavy user of ICT. Of particular importance is the stream of research originated by the construction of industry-level productivity data in the KLEMS project, supported by the European Commission (O'Mahony and Timmer, 2009; Timmer *et al*., 2010). Inklaar *et al*., (2003) and Timmer and van Ark (2005) found that the US lead in labour productivity is almost fully explained by two causes, both related to ICT: the deepening of ICT capital and the increase in total factor productivity originated from the production of ICT goods. O'Mahony and Vecchi (2005) also found a strong effect of ICT on the overall growth of output in the case of the USA. In the summary words of Van Ark *et al*. (2008: 41):

> …the resurgence of productivity growth in the United States appears to have been a combination of high levels of investment in rapidly progressing information and communications technology in the second half of the 1990s, followed by rapid productivity growth in the market services sector of the economy in the first half of the 2000s. Conversely, the productivity slowdown in European countries is largely the result of slower multifactor productivity growth in market services, particularly in trade, finance, and business services.

A related body of literature has investigated the complementarity between investment in ICT and organizational change in companies, again pointing to a gap between US and Europe (Bloom *et al*., 2007; van Reenen and Bloom, 2007).

In general, the computer technology is considered a classical example of a general purpose technology, whose impact on the economy is pervasive, transversal, and deep (Bresnahan and Trajtenberg, 1995). Ten Raa and Wolff (2000) identified the sectors that are most responsible for the growth in total factor productivity in the period 1958–1997 in the USA, and discovered that the sectors accounting for the largest effect were computer and office equipment and electronic components. In addition, these sectors showed the largest spillover effects to other industries, including services (Mamuneas, 1999). For these reasons the weakness of the European industry is generally considered with concern.

But why did the US economy adopt ICT earlier and more productively, first in the manufacturing sector, then in the market service sector? An interesting question is whether (but also why) there is a relationship between the performance of domestic ICT-goods producers and the spread of adoption of ICT in non-ICT sectors. This link is not at all obvious. The better performance of US ICT-goods producers might have also benefitted European adopters, albeit with a short delay. As we will see, this issue can be better explained within the framework offered by this paper.

In search of an explanation for the competitiveness gap

There are several possible explanations for the competitiveness gap suffered by the European IT industry (we now turn back to the narrow definition). First, the role of military procurement and defence-related R&D should not be overlooked. Many technological breakthroughs, including the original idea of the internet, originate from this source (Flamm, 1988; Lowen, 1997). Since the USA devoted a large share of R&D to military uses, it is reasonable to expect positive spillovers in the IT industry (Alic *et al*., 1992). Second, one might call attention to the dramatic role of large national markets in the establishment of technological standards. Since almost all IT-based industries are subject to strong network externalities, once standards are established a lock-in effect would give the leaders a long-term advantage. The case of Microsoft in operating systems is an obvious example. Not surprisingly, in mobile phone technology Europe gained a leadership position also because of a first mover advantage in defining the global system for mobile communications (GSM) standard. Thus market size may be considered a natural advantage for US industry, one that cannot be modified by will (Mowery, 1996; Campbell-Kelly, 2003). Third, one might refer to the linguistic heterogeneity of European countries to explain the difficulty in producing standardised or packaged products in software. According to this interpretation, European software companies would be globally competitive, but they specialize in customised software products, which require adaptation to the customer and the use of national languages. In addition, European markets are still fragmented in terms of regulation (particularly in services), standardization and professional practices, creating obstacles to international expansion of firms, increasingly to young innovative firms (Conway and Nicoletti, 2006). Fourth, the corporate model is also relevant: many European players in IT in the 1980s and 1990s were vertically integrated companies in large conglomerates which were not responsive to the stock exchange market, which developed IT mainly for their internal corporate, that is, captive, market. This was a major long-term strategic mistake, insofar as it insulated IT business units from harsh competition in global markets (Becchetti, 2001). Vertical conglomerates in countries with rigid labour markets tend to keep obsolete technologies alive for longer periods.

All these explanations have some truth in them and should be carefully considered. It is not the purpose of this paper to review the debate on European

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competitiveness in the IT industry. Rather, we wish to suggest another factor, which has been somewhat neglected in this debate. We suggest that the long-run origins of competitiveness in a high technology industry are to be found in the excellence of the underlying scientific base. This does not translate at all linearly into new products and services. Much more than that, it nurtures the ecology of ideas and visions that give origin to innovation. There is a hidden link between the quality and dynamics of scientific research in the underlying fields, particularly computer science, and industrial competitiveness. We will use original evidence, admittedly of preliminary type, to support this proposition.

In the second section we will review some of the most important technological innovations in the IT industry and relate them to their intellectual origin. This sets the stage for the third section, in which we propose a theoretical framework to articulate the relation between the dynamics of scientific knowledge (or search regime) and the industrial competitiveness. In the fourth section we review descriptive evidence drawn from a large sample of CVs of the top 1,010 scientists in computer science worldwide. Finally, we illustrate some policy implications of these findings and draw conclusions.

Technological competitiveness and long-term scientific performance: a neglected link?

On the origin of ideas in the IT industry

By any standard, the IT industry has witnessed an impressive record of technological progress after World War II (WWII). As Gordon Moore once noted:

> …if the transport industry had the same rate of progress, it would now be possible to fly from New York to Paris in a few minutes.

The IT industry is now a huge collection of specialised and interdependent industries, each of which has its own established markets, end users, performance criteria, and learning curves.

What is the relationship between technological progress in this industry and scientific progress in underlying fields? This is not an obvious question, particularly after careful economic theorizing and many historical and empirical reconstructions have demolished the myth of a linear transition between scientific discovery and technological development.

Let us start with a preliminary investigation, based on expert opinion. A few years ago we asked a small panel of scientific authorities in computer science, in both European and US universities, to list the most important technological innovations in the industry after WWII and to identify the origins of the idea. Their opinions are valid still today.

Table 1 shows the list of top 10 innovations. Quite surprisingly, although eventually developed by companies and introduced to the market, all of them can be traced back to genuine new ideas originally conceived in the academic world. Although there may be a bias in this reconstruction, due to the professional background of our respondents, what is mentioned is not a pure academic outcome but technological breakthroughs, eventually transformed into huge worldwide market opportunities.

There is another useful piece of information in Table 1. With the (partial) exceptions of the early pioneering ideas of John von Neumann and of the invention of the internet at CERN, all the major breakthroughs originated from academic research carried out by US scientists and/or in US universities. Put it into a historical perspective, while the seminal theoretical contributions to the entire field of computer science were conceived by European thinkers (Alan Turing and John von Neumann) the evolution of the field in the half-century after WWII has been dominated by US scientists.

This evidence suggests that the linkage between technology and intellectual creativity might be much deeper and subtler than is possible to detect with classical economic indicators, such as citations in patents, or R&D expenditure. We must develop new approaches to carefully trace the flow of ideas from

Table 1. Origins of most important ideas in computer science and technology

Top ten ideas in computer science
1. Turing machine (Goldstine and von Neumann; Turing)
2. Programming languages; formal description of syntax and semantics; LISP (McCarthy)
3. Memory hierarchy; cache memory
4. User interface; graphic user interface (GUI); concept of window (Xerox Palo Alto Research Center; Apple)
5. Internet (UCLA/DARPA); packet switched multinetworks; http and html protocols; WWW (Berners-Lee)
6. Computational complexity; computational intractability; pseudocausality
7. Relational database
8. Fourier fast transform (FFT) (Cooley and Tuckey)
9. Efficient algorithms; data structure (Knuth and Tarjan)
10. Artificial intelligence

Source: our elaboration from expert opinion the mountains of pure theory down to the sea of market competitiveness. We know that the path is not linear, but then we ignore how to trace commercial success back to the pioneering ideas. The incubation cycle of truly innovative ideas may be very long.

Luckily, computer science and the computer industry have been the object of a massive historical literature, that has highlighted several key factors. We draw from this literature to answer the following research question: To what extent do the technological performance and the industrial competitiveness of the IT industry depend on the quality of the underlying science? The answer to this question is preliminary to another one: To what extent can the poor performance of the European IT industry be traced back to the poor performance of its scientific base?

Historical reconstructions are absolutely clear about the dominant role of private companies, the importance of demand from the military and the civilian business, and the importance of scale and scope, or the complementarity between technology, manufacturing and marketing investment by large companies such as IBM (Flamm, 1988; Chandler, 1990; Langlois, 1992; Mowery, 1996; Langlois and Steinmuller, 1999). Historical records of inventions in computer technology show a disproportionate share of contributions from companies (see Dummer (1997) for a broader reconstruction covering all fields of electronic inventions and discoveries). At the same time, they open several windows onto the underlying dynamics of knowledge generated in academia. As succinctly stated by Mowery and Rosenberg (1998: 140):

> University research played a key role in the growth of the US computer industry. Universities were important sites for applied, as well as basic, research in hardware and software and contributed to the development of new hardware. (…) By virtue of their relatively 'open' research and operating environment that emphasized publication, relatively high levels of turnover among research staff, and the production of graduates who sought employment elsewhere, universities served as sites for the dissemination and diffusion of innovation throughout the industry.

We briefly review some of the turning points in the history of computing in which this contribution is more evident. Evidence on the USA is offered first, followed by evidence on the role of the European public research sector.

Historical evidence on the role of the scientific base: USA

The era of digital computing in the USA was inaugurated by the ENIAC electronic calculator (Ceruzzi, 1998; Norberg, 2005), which was designed and built at Moore School of Electrical Engineering, University of Pennsylvania by Eckert and Mauchly, during WWII, to meet a requirement for calculating firing tables for the US Army. After this development, in 1945 the great mathematician John von Neumann described the abstract structure of a modern computing machine, which eventually became universally acclaimed as the von Neumann architecture. Before that, IBM had developed the automatic sequence-controlled calculator (ASCC), known as Mark I, which was still an electromechanical machine. It came out in 1944, resulting from on a joint effort between IBM and the University of Harvard, which was established in 1939 (Moreau, 1984).

Interestingly, as early as in 1946 the Moore School of the University of Pennsylvania and the US Army sponsored a course on the theory and techniques for the design of electronic digital computers. However, the role of the university was not unambiguous: in the same year one administrator of the Moore School:

> …asked that members of the staff sign a release form that would prevent them from receiving patent royalties on their inventions. He brooked no discussion. Eckert and Mauchly refused to sign. They resigned on March 31, 1946. (Ceruzzi, 1998: 25)

Eckert and Mauchly soon established a company that developed the UNIVAC, the first large-scale computer, which was sold to the military, the Census Bureau, and to private companies for administrative uses. In the 1950s several companies entered the industry. IBM hired von Neumann as a consultant in January 1952 and started a collaboration with his organization, the Institute for Advanced Study at Princeton (Pugh, 1995). Another company, Engineering Research Associates, starting from code-breaking activities during WWII, hired engineers from the University of Minnesota, among whom was Seymour R Cray, who eventually became a leader in supercomputing. Another small company, Bendix, built the G-15 computer, based on Harry Huskey's 1953 design at Wayne State University, Detroit, MI. Thus in the early days of the computer industry we witness many universities building their own machines, based on von Neumann or Turing architectures.

The role of universities greatly increased after a commercial move by IBM. In 1954 IBM delivered the 650, a machine that was installed mainly for business purposes in a thousand companies. Thomas Watson Jr decided that a university could benefit from a discount up to 60% on the price of the 650 if that university agreed to offer courses in business data processing or scientific computing (Watson, 1990). This opened the way to a large diffusion of courses in computer science across US universities.

Meanwhile, US universities started to be involved in research on the component technologies underlying the computer. Soon after WWII, the University of Illinois, Harvard and Massachusetts Institute of Technology (MIT) worked on magnetic core memories (Pugh, 1984; Wildes and Lindgren, 1985). Bassett (2002) has shown that even in industrially sensitive fields such as metal-oxide semiconductor technology, large companies left their researchers relatively free to publish papers and to attend scientific conferences, thus interacting with academic researchers.

The role of academic research is also evident in the field of high-level programming languages, for both the USA and Europe. While the single most important language, FORTRAN, was invented by John Backus at IBM in 1954 (Pugh, 1995), the APT language for the control of machine tools was developed by the Servomechanisms Laboratory of MIT in 1955, the ALGOL 60 was created by a committee convened by F L Bauer from the University of Munich (Germany) in 1958, and COBOL was promoted by a group of universities and computer users which held a meeting at the Computation Center of the University of Pennsylvania in 1959. In turn, the LISP language was developed by John McCarthy at MIT in 1958 (Moreau, 1984), PASCAL was developed by Niklaus Wirth at ETH in Zurich (Switzerland) in the period 1968–1969 (Wirth, 1996) and PROLOG was born in 1972 after the work of several French researchers mostly based at the University of Marseille (Colmerauer and Roussel, 1996). As with C++, it was developed in 1979 at Bell Laboratories by Bjarne Stroustrup, on the basis of the work he did for his PhD at Cambridge University (UK) (Stroustrup, 1996).

Academic excellence was not necessarily an ingredient, however, particularly after the development of the software industry. In December 1968 IBM was forced by the US authorities to unbundle the commercialization of software from sales of hardware products, giving origin to a separate industry, which then propagated in several application areas (Mowery, 1996). In many cases the development of software was the product of a large-scale entrepreneurial effort, carried out by thousands of individual programmers. As Campbell-Kelly (2003: 209) puts it:

> In the late 1970s, a typical software development firm consisted of one or two programmers with strong technical skills but no manufacturing, marketing or distribution capabilities.

This trend was reinforced after the emergence of the personal computer (PC) in the 1980s, but also in the huge growth of the videogame industry and of software applications after the internet revolution. The creative skills of small firms were commercially exploited by larger firms, or the former were acquired, or disappeared. Universities did not play a direct scientific role in this massive bottom-up effort, but were a crucial element for the mass culture that fostered entrepreneurial activities:

> In the software industry, most of the R&D is done by youthful programmers, usually not trained past the bachelor's degree level, who crank out code in an intuitive but effective fashion. (Campbell-Kelly, 2003: 308)

Programmers do not necessarily come from postgraduate studies at universities, but benefit from an environment in which new ideas are generated and debated on a continuous basis. Without such an academic background it would not be possible to explain the hacker movement, or the explosion of creativity over the concept of PCs illustrated by popular books such as Levy (1984) or Freiberger and Swaine (1984).

A similar line of interpretation has been proposed in an effort to explain the impressive success of Silicon Valley. According to an influential historical literature, it was the top quality research carried out at Stanford University that gave origin to the birth of the electronics industry (Leslie, 1992; Leslie and Kargon, 1996). In particular, Frederick Terman, dean of the School of Engineering and then provost at Stanford, promoted large military patronage in electronics and then supported graduate engineers in the creation of new corporations (for a critical view, see Lowen, 1997). Other studies have confirmed, but also mitigated, this explanation. Kargon *et al.* (1992) consider a broader complex of academia, industry and government actors. Lécuyer (2006) has shown how Stanford students benefitted from updates in technology provided by companies located in the area, creating two-way technology flows.

The role of military procurement for the growth of computer technology cannot be understood only on the basis of a demand–pull mechanism. Much more than that has been occurring. The design of research activities for the military has historically nurtured a complex interaction between academic research and procurement needs. Norberg and O'Neill (1996) have studied the creation and activities of the Information Processing Techniques Office (IPTO) at the Defense Advanced Research Projects Agency in the period 1962–1986. They note that:

> IPTO's early program emerged from the goals and desires of (…) university researchers eager to investigate new computing techniques.

Throughout its entire life, IPTO followed the rules prescribed by its early director, Joseph C R Licklider, that the first criterion to be used for selection of projects was that:

> …the research must be excellent research as evaluated from a scientific or technical point of view. (Norberg and O'Neill, 1996: 29)

As another source describes the arrangement:

> Licklider developed an effective way of administering the IPTO program, which was to place

> his trust in a small number of academic centers of excellence that shared his vision- including MIT, Stanford, Carnegie Mellon, and Utah- and give them the freedom to pursue long-term research goals with a minimum of interference. (Campbell-Kelly and Aspray, 2004: 191)

Thus the crucial point is that military procurement of research reinforced criteria of scientific excellence, which were not to be sacrificed for purposes of short-term utility.

Universities changed their role in the early history: in the heroic period until 1959 they were directly involved in full-scale design and prototype production of computers, while after the emergence of a dedicated computer industry they were rather committed to fundamental research, education, scientific advice and consultancy.

Historical evidence on the role of the scientific base: Europe

During WWII all large European countries had a promising start with the computer industry and built up foundations that could evolve into industrial competitiveness. Indeed, the origins of the computer technology are to be found in 20th century European science, particularly in the work of two intellectual giants: Alan Turing and John von Neumann. The reasons why an intellectual advantage did not turn into industrial competitiveness are worth exploring in detail. In the case of Europe, the role of universities must be considered jointly with large public research organizations (PROs), such as Max Planck in Germany, or CNRS, INRIA and CNET in France. We focus on three large European countries: the UK, France, and Germany.

In 1937 the English mathematician Alan Turing published the first theoretical model of a modern computer, the universal Turing machine (Davis, 2000). He had visited Princeton in 1936, where he met the great logician Alonzo Church and von Neumann, who in 1938 offered him a position. Turing declined and went back to Cambridge, and during WWII played a great role in the production of a digital computer, known as COLUSSUS, which was developed as early as in 1943 for military use (Randell, 1980; Lavington, 1980a) and kept secret for many years (Copeland *et al*., 2006). One of the main reasons why the UK did not capitalize on its early achievements in digital computers was that these machines were considered military secrets and were dismantled after WWII. In 1945 Turing joined the new Mathematics Division of the National Physical Laboratory, where he contributed to the development of the automatic computing engine (ACE), which was realized in 1950 and was the basis of a commercial version which was sold in the period 1955–1964 (Moreau, 1984). Two university groups were active in that period in the UK, one at Manchester and another at Cambridge. As early as 1948 a prototype of the first completely electronic stored-program computer, conformed to the von Neumann architecture, was completed and labelled the Manchester automatic digital machine (MADM) (Lavington, 1980a; 1980b). It went into operation in 1949. In the same year the electronic delay storage automatic computer (EDSAC) was realized at Cambridge. Here Maurice Wilkes developed ideas that prepared for high-level programming languages, such as symbolic labels, macros, and subroutine libraries (Books LLC, 2010a). Thus in the early years of the computer era the UK was head-to-head with the USA. Ironically, as Moreau notes:

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> …it was the Europeans rather the Americans who were the first in the world to make a computer as a commercial product. (Moreau, 1984: 53)

It was the Ferranti MARK I, built in collaboration with the Manchester University Group and delivered in 1951. A commercial computer, known as LEO, was installed at a company in 1951, well before ENIAC (Campbell-Kelly, 1989; Ceruzzi, 1998).

In France the theoretical roots of computer science were laid down as early as the 1930s. The French mathematician Louis Couffignal demonstrated how a programmable binary calculator could be constructed using electromechanical technology as early as 1938, but his contribution was not well understood by the scientific environment (Moreau, 1984). The first machines were realized in the 1950s. The Bull Company's prototype of Gamma 2 was shown at the international exhibition in Paris in 1951, while the Calculateur Universal Binaire de l'Armament (CUBA) was delivered to the military by the Societé d'Electronique et d'Automatisme in 1952. Bull's Gamma 3, developed in 1952, was also a commercial success, with more than 1,000 units sold (Leclerc, 1990; Moreau, 1984). In 1945 SEA introduced the CAB 2000 series, one of the first to use ferrite-core memories. According to Mounier-Kuhn, 1994: 214):

> …in 1960 Compagnie des Machines Bull was one of the world's leading manufacturers of data processing machinery. It had a base of

> over 4,000 installations, of which a third were exported; 14,000 employees in France, ten factories, and a global turnover of 201 million French Francs, which had multiplied by 10 over the past 10 years.

Bull with the Gamma 60 was one of the competitors for the tender issued by the US Atomic Energy Commission (AEC) for a machine 100 times faster than any then existing, alongside UNIVAC and IBM. Unfortunately, although highly innovative, the machine had several problems that would have required substantive development, and failed to gain market share. These companies used to establish strong linkages with universities, particularly in Paris and Grenoble, and PROs.

The link between academic research and industrial production is also evident in the case of Germany and other German-speaking countries such as Switzerland and Austria. Here the construction of computers started with the pioneering work of Konrad Zuse well before WWII. Zuse started his efforts in 1936, developed the Z1 binary calculator in 1938, the Z2 mechanical calculator in 1939 and the Z3 relay calculator in 1941 (Zuse, 1980; Swedin and Ferro, 2005; Rojas, 2006). After WWII he established the Zuse KG company. In addition, the scientific foundations for the modern notion of software were established by academic groups in the 1940s and early 1950s. These included: the Plankalkül of Zuse in 1945, the work of Rutishauer and Bohm in Zurich in 1951, and the work of Semelson and Bauer in Munich in the 1950s (Bauer, 2002). Semelson studied the structure of programming languages and developed the notion of bracketed structures, a fundamental breakthrough in computer science, while Bauer was the first to propose the stack method of expression evaluation. Jointly, they developed fundamental works on compilers (Books LLC, 2010b).

Indeed, Zuse's work is considered by historians of computing technology to be the earliest pioneering work in the modern era. In his reconstructions of major early computing events Williams places European pioneers such as Zuse, Turing at NPL, Williams and Kilburn at Manchester and Wilkes at Cambridge alongside von Neumann, Eckert and Mauchly, the Moore School, Harvard University, IBM and the Bell Laboratories in the USA (Williams, 2000). In the early history of computing technology Europe and the USA were equally competitive.

These short summaries also make it clear that the early era of computer technology saw the deep involvement of the academic environment. Initially, universities were directly involved in the production of prototypes. With the advent of the 1960s, the heroic period of prototype building was over and large computer manufacturers emerged. However, a sharp difference seems to emerge between the evolution of the technology in the USA and Europe. In the USA, this structural change did not bring a diminishing role for universities, but a redesign or their role around fundamental research, education, scientific advice and consultancy. In Europe, the academic environment was leading head-to-head with the US one until the 1960s, but it seemed to lose ground in the subsequent decades. Not many scientific stars from Europe are mentioned in the studies of history of computing after the 1970s. This is an interesting puzzle. It is clear that the institutionalization of computer science as an academic discipline took place earlier in the USA, approximately in the 1950s, than in Europe, where it started in the late 1960s and diffused in the 1970s. But this is in itself part of the question: Why was the European academic system, which had generated pioneering achievements since the 1930s, so slow to accommodate the new discipline institutionally? We suggest that a deep exploration of this puzzle might shed light on the overall issue of the long-term competitiveness of the European IT industry.

In search of an explanation: characterizing the search regime of computer science

In a stream of recent papers (Bonaccorsi, 2007; 2008; 2010; Bonaccorsi and Vargas, 2010) we have argued that robust policy implications must be based on the comparative analysis of search regimes, or the characteristics of the dynamics of production of scientific knowledge. Scientific fields differ in the challenges they pose to institutions of science at national level, so that their long-run performance depends on how national scientific systems adapt to them (Bonaccorsi, 2011). It is therefore useful to try to characterize the history of computer science from the point of view of the underlying abstract dynamics of knowledge.

The National Research Council (NRC) of the US National Academies has edited a number of essays from leading scientists on the state of the art of computer science, with a collective introduction (NRC, 2004). The opening description sets the stage for our discussion:

> Computer science embraces questions ranging from the properties of electronic devices to the character of human understanding, from individual designer components to globally distributed systems, and from the purely theoretical to the highly pragmatic. Its research methods are correspondingly inclusive, spanning theory, analysis, experimentation, construction, and modelling. Computer science encompasses basic research that seeks fundamental understanding of computational phenomena, as well as applied research. The two are often coupled; grappling with practical problems inspires fundamental insights. (NRC, 2004: 11)

This description is interesting for several reasons. To start with, it is not based on the classical dichotomy between pure and applied science. Differently from physics, where theoretical physics is often detached from experimental physics, in computer science there is a significant overlap. Great theorists also engage in developing (or have their students develop) software code in order to test their results. This is facilitated by the fact that the test of theories can be done in a relatively cheap way, by writing and running programs, instead of doing experiments in laboratories.

Second, application is not just application, but is the source of inspiration for 'fundamental insights'. This means that those that bring new problems to the scientific community are not considered to be the final point of the application chain, but are themselves part of the discovery process. This has important institutional consequences, insofar as the scientific community not only includes academicians, but also company scientists, engineers, technicians and managers. The professional boundaries between academia and industry are blurred. Mobility between the two worlds is mandated by the content and practice of research.

There is a deep epistemic reason for why fundamental research has been so important for the development of IT. As the introduction states succinctly, computer science research (NRC, 2004: 15):

> …involves symbols and their manipulation and the creation and manipulation of abstractions.
>
> …creates and studies algorithms and artificial constructs, notably unlimited by physical laws.
>
> …exploits and addresses exponential growth.
>
> …seeks the fundamental limits on what can be computed.
>
> …focuses on the complex, analytic, rational action that is associated with human intelligence.

This explains why fundamentally new ideas on technology are often the product of academic environments, populated with visionary professors, hardworking PhD students, brilliant undergraduate students, rather than of corporate laboratories. The role of abstraction is crucial here. In technical terms, abstraction means that there are sets of definitions that make it possible to manipulate the same object (e.g. procedures, or data) at many levels, preserving its fundamental properties. This makes it possible to move increasingly far from the physical implementation on a hardware without losing the relevant aspects of the description. For example, it is possible to decouple the program from the underlying hardware representation (Shaw, 2004). This is sharply different from what happens in most areas of engineering (as well as in the human brain). It would not be possible to ignore the detailed physical and geometric conditions of, say, materials, in the design of a mechanical structure: here the study of mechanical properties, stability, elasticity or dynamics requires different tools and methods, but none of them can be done by abstracting from the specific features of the designed body and without physical testing. As a prominent theoretical computer scientist summarized:

> The computer originated in the academic environment. Zuse and IBM are special cases. From the Moore School and the University of Iowa, from Aiken and Wilkes to Algol, the vast majority of the essential steps were achieved on academic grounds. Neither the car nor the aircraft have come up this way. And there are very good reasons. One certainly is that the computer has an essential abstract side, most visible in programming, and abstract automatization is at least not a usual industrial subject. (Zemanek, 1997: 16)

To illustrate the power of abstraction, the introductory essay in the NRC's volume notes that:

> …the Internet works today because of abstractions that were products of the human imagination. Computer scientists imagined 'packets' of information flowing through pipes, and they (symbolically) worked out the consequences of that idea to determine the new laws those flows of information must obey. This conceptualization led to the development of protocols that govern how data flows through the Internet, what happens when packets get lost, and so on. (NRC, 2004: 18; see Peterson and Clark, 2004)

The discussion above can be summarized using the notion of a search regime (Bonaccorsi, 2008). According to this notion, the dynamics of production of knowledge in scientific fields can be characterized along three dimensions: the rate of growth, the dynamics in knowledge diversity, and the nature of complementarity. On the basis of an extensive historical reconstruction and of informed reports from scientists, we can conclude that the search regime of computer science has been characterized by turbulent

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The large rate of growth and the divergent dynamics (proliferation) derive from the intrinsic epistemic dynamics. On one hand, after the emergence of microelectronics Moore's law (which is not a law of nature, but a law of business), granted order of magnitude increases in computing power over time, relaxing year after year the constraints on computation. At the same time, the symbolic representational nature of computer programs made it possible to explore hundreds of different directions at relatively low cost. Programming languages added further diversity to the search regime, by allowing computing results to be obtained in many different programming ways. The abstract nature of computer objects (e.g. data, procedures) allowed a process of progressive transformation of many fields of reality, previously represented in analogical ways, in the form of bits. This has triggered a proliferation dynamics, whereby, at any point in time, there have been several diverse research trajectories, sometimes also in competition, rather than convergence on a few research programmes (Bonaccorsi and Vargas, 2010).

The nature of complementarity also comes from the epistemic dynamics. The progressive digitalization of regions of reality (not only data but images, sound, movement, all sorts of physical parameters etc.) has attracted a large number of other disciplines into computer science, creating powerful forms of cognitive complementarity. Not only mathematics, logics, and electric and electronic engineering have been involved into computer science since the beginning, but also biology and chemistry (bioinformatics), earth sciences (geographic information systems), psychology (artificial intelligence), visual art (computer graphics), operations management (enterprise resource planning), and many other cognitive fields. All have been deeply transformed from the relationship with computer science. In all cases, there was not just 'application', but, as noted above, 'fundamental insights' to be gained from this complementarity.

Another form of complementarity is defined institutionally, i.e. the systematic interaction between scientific and non-scientific institutions, such as industry, hospitals, government. In computer science, this complementarity comes from the constitutive interplay between theoretical work and pragmatic goals (Bonaccorsi, 2010).

A crucial point is that this process is dynamic and self-reinforcing. Building up an attractive scientific environment requires obsessive attention to quality criteria in recruitment and promotion of academic staff, as well as ambitious goals in the selection of students. The two reputational processes reinforce each other and make it credible to raise government or private money for research.

Summing up, we see considerable evidence of intense exchanges of ideas and knowledge flows between industry, academia and government. Although it cannot be said that university research has been the source of most inventions, it has played a prominent role in creating new concepts and ideas, in maintaining a challenging intellectual climate, and in supporting the entrepreneurial attitude of students and graduate researchers. Also, deep and radically new ideas often originated in academic environments, were incubated for some years, and eventually found their way into innovations in the market.

We are then faced with our two research questions. First, is there a systematic relationship between quality of academic research and industrial competitiveness in IT? If the answer is yes, then there is a second question: Is there a structural difference between Europe and the USA in this respect? In order to address these questions we now present fresh empirical evidence and then build up an explanation.

New evidence on scientific excellence in computer science

An analysis of the CVs of top computer scientists

An interesting perspective is to look at the large community of computer scientists and at their own self-validation processes. Citations to papers in computer science are automatically recorded by Citeseer,[2] a highly structured indexing system established in 1997 and endorsed by most scientific societies and departments in computer science worldwide. The Citeseer service ranks scientists by the total number of citations, without checking for homonyms and controlling for the age of scientists. Therefore it may be considered a crude approximation for more sophisticated bibliometric exercises. However, over large numbers the probability and size of errors are considered acceptable.

We downloaded from the internet all CVs of all top 1,000 scientists in the Citeseer service, as of end 2005 (more precisely, n = 1,010). These scientists have the largest cumulative number of citations in papers from a list of journals and conferences in computer science, irrespective of their age. Their average age is 56 years, with a minimum of 30 years. CV downloading and data processing was done manually by a team of research assistants.

Information from CVs is well known to be highly informative and rich, but is usually not valid and is statistically difficult to treat. Self-declaration cannot be checked with any accuracy. The updating of information is totally arbitrary. The format is free and practical experience shows many instances of arbitrariness and bizarre attitudes. Thus there is often no way to fill in missing information from any other source. In a few cases we had to address the scientists by mail, in order to check for missing information, but not always with success.

We therefore decided to focus mainly on hard information, in which the incentive to misrepresent reality may be low. Several items of data are still missing, so the analysis must be done on different samples, variable by variable. A number of interesting insights can be derived from this type of information. Looking at the top scientists at the top their career and recognition is a useful way to reconstruct the history of scientific achievements in the last half-century. What follows is a purely descriptive treatment of data, with limited comment.

It is almost impossible to rank high in the computer science field without a PhD from either the USA or Europe, with the USA leading by a large margin

Patterns of educational mobility

We identified the location of the universities at which top scientists received their academic degrees. Such information can be retrieved with certainty for 855 scientists in the case of PhD, 457 for the Master degree and 641 for the Bachelor degree (see Table 2).

In terms of information availability, it is likely that not all scientists received a Master degree, which is not formally necessary to receive the PhD in several academic systems. In turn, the difference between the total number of observations for PhD and the size of the sample (855 vs 1010) may be due to people without a PhD degree or to people not mentioning the place of their degree. It is impossible to disentangle the two effects. Furthermore, it is possible that some scientists do not mention the place of their first degree, which is a necessary preliminary to receiving a PhD.

The geographic distribution of PhDs is extremely concentrated: US universities gave the degree to future top scientists in 76.5% of observable cases, against 16.6% in the case of Europe. This gives an extremely accurate view of the type of tough competition in this community: it is almost impossible to rank high in the computer science field without a PhD from either the USA or Europe, with the USA dominating by a large margin. A similar level of concentration can be observed in the case of Master degrees. These degrees require a great deal of international mobility and tend to be considered a first step towards the PhD for talented students. Very interestingly, the geographical distribution is much less concentrated in the case of Bachelors. Here a good 15% of students come from Asia and 10.9% from other countries. It seems that the US academic system has been historically able to attract talented graduate students from all over the world, offering Master and PhD degrees as intermediate steps towards a scientific career.

In evolutionary terms, it seems that the US academic system has superior properties of variety generation, in the sense that is able to identify, select, and motivate a continuous flow of intellectual talent, irrespective of the culture of origin, to be channelled into a powerful system of selection and retention.

Additional insights can be obtained by examining the time evolution of PhD degrees. We obtained information on the year of receiving their PhD for 719 scientists. Note that the place of PhD degree is instead recorded in 855 CVs (see below). We decided not to compute the date in a conventional way, for example by adding a fixed number of years to the birth date, or similar interpolation techniques.

For this sub-sample of 719 scientists, we observe (see Table 3) an extremely skewed distribution of the place of degrees, with the USA representing 77% of the total and Europe 16%, five times less. In terms of cohorts, it is interesting to observe that by end of the 1960s the US universities had already granted 89 PhD degrees to those that eventually became top scientists. After that, there is a progression in the number of degrees in US universities, while the same is not true for European universities. This finding sheds light on the puzzle identified in the section of this paper on ‘Technological competitiveness and long-term scientific performance: a neglected link?’: while Europe was at the leading edge in the 1950s, it gradually lost ground. The consequences of this weakness rapidly became visible. In the period 1980–1989, a period of explosion of computer science and information technology, US

Table 2. Distribution of degrees of top computer scientists by geographical area

Area	PhD degree		Master degree		Bachelor degree	
	Number	%	Number	%	Number	%
USA	654	76.5	332	72.6	363	56.6
Europe	142	16.6	58	12.7	112	17.5
Asia	9	1.1	30	6.6	96	15.0
Other	50	5.8	37	8.1	70	10.9
Total	*855*	*100.0*	*457*	*100.0*	*641*	*100.0*

Table 3. Distribution of year and place of PhD degree of top scientists in computer science

Year	USA	Europe	Asia	Other	Not available	Total
< 1950	4	4	0	0	0	8
1950–1959	19	3	0	0	0	22
1960–1969	66	9	2	3	0	80
1970–1979	134	48	1	10	0	193
1980–1989	207	37	4	18	2	268
1990–present	122	17	1	7	1	148
Total	552	118	8	38	3	719

universities were able to attract 207 high potential candidates (+55% with respect to the previous decade), against only 37 at European institutions (−23%). Something must have happened in that period, probably a manifestation of the accumulation of weaknesses.

It is highly informative to examine the identity of those universities that granted undergraduate and postgraduate degrees to those brilliant scientists in their early days. Again, we focus on the upper tail of the distribution of universities, because we are more interested in understanding the dynamics at the extreme, rather than the average properties. This is more informative about the real conditions of mobility and capacity building in a highly turbulent scientific field.

Therefore we select the top 15 universities in which the top scientists have received their degree, at each of the three levels of education, i.e. PhD, Master, and Bachelor (see Table 4), in descending order for the PhD.

The top 15 universities represent 56.2% of all universities granting a PhD to the 855 top scientists for which we are able to reconstruct the information. In turn, the top 15 universities represent 47.1% of those granting the Master degree (n = 457) and 41.3% of those granting the Bachelor (n = 641). The differences in the coverage rate shows that postgraduate education is more concentrated than undergraduate. Nevertheless, the top 15 universities cover between 40% and almost 60% of the sample, a reasonable proportion for our analysis.

We start from PhD education. A few comments are in order. First, the top ranking covers mostly US universities, with two Europeans featuring in the 10th position (Cambridge, UK) and 14th position (Edinburgh, UK) and a Canadian one in the 13th position (Toronto). Second, the distribution is highly concentrated. As stated, the first 15 universities attract 56.2% of all scientists for whom we have full information. But this is not enough: the first four (MIT, Stanford, Berkeley, Carnegie Mellon) attract

Table 4. Ranking of top 15 universities granting PhD, Master and Bachelor degrees to top scientists in computer science

	PhD degree		Master degree		Bachelor degree	
	Number	%	Number	%	Number	%
MIT	82	9.6	47	10.3	45	7.0
Stanford University	78	9.1	29	6.3	10	1.6
University of California at Berkeley	69	8.1	27	5.9	20	3.1
Carnegie Mellon University	43	5.0	13	2.8		
Harvard University	35	4.1	14	3.1	25	3.9
Cornell University	27	3.2	12	2.6	11	1.7
Princeton University	26	3.0			15	2.3
University of Illinois	22	2.6	12	2.6		
University of Michigan	20	2.3	9	2.0	18	2.8
University of Cambridge	16	1.9			18	2.8
Yale University	15	1.8	7	1.5	14	2.2
University of Wisconsin	14	1.6	10	2.2		
University of Toronto	13	1.5	7	1.5	9	1.4
University of Edinburgh	13	1.5				
University of Pennsylvania	13	1.5				
University of Massachusetts			8	1.8		
University of Washington			7	1.5		
University of California at Los Angeles			7	1.5		
Indian Institute of Technology			7	1.5	34	5.3
National Taiwan University					13	2.0
California Institute of Technology					12	1.9
Technion Israel Institute of Technology					11	1.7
Brown University					10	1.6
Total number of observations	855		457		641	

Note: universities not in USA are in italics almost one-third of the total. Third, a mutual reinforcement mechanism is clearly in place. Brilliant students target top universities because there they have the opportunity to meet and to work with the best scientists. Top universities actively target talented students to confirm their reputation. Postgraduate education seems to be a promising candidate to explain the success of the scientific careers of these scientists. Understanding the extraordinary success of the US PhD model in turbulent fields is therefore a key for policy learning.

When examining the distribution of universities granting the Master degree the top list is slightly different. There are a few new entries from the USA (e.g. University of Massachusetts and University of California at Los Angeles), but the most interesting new entry is the Indian Institute of Technology, which is not a single institution but an umbrella organization for several universities.

The situation changes quite drastically when we move to the Bachelor degree, the entry point for students considering a career in computer science. In this list the Indian Institute of Technology ranks second, contributing with 34 undergraduate students to the flow of future star scientists. Interestingly, here we find many more universities outside the USA: from Europe (Cambridge), Taiwan (National Taiwan University), Israel (Technion Institute of Technology) and Canada (Toronto).

Our interpretation is as follows. The talent pool for a career in computer science is worldwide. Entry points are good universities offering strong basic scientific knowledge but also giving brilliant students sufficient motivation to emerge. After that stage, however, future top scientists must be channelled into foreign universities, most of which are in the USA. In preparing for this migration of talent, Asian countries have been more strategic, investing heavily into the preparation of undergraduate students to be selected and sent to top US universities. European universities, in contrast, cultivate the ambition to organize graduate education, particularly PhD education, in isolation. They actively practice endogamy, by selecting students from internal Master programmes, which in turn select bright students from the Bachelor. With few exceptions, European postgraduate education in computer science is not globally competitive. If it were competitive we would see more students migrating from Asia and the rest of the world into Europe, instead of the USA, and we would see more students moving from the USA to Europe. In other words, Europe seems to play a game of limited mobility.

Patterns of disciplinary mobility

Where do top computer scientists come from, in terms of disciplinary affiliations? The data do not allow a full-scale analysis, because we do not have control samples of scientists in related fields. Therefore the evidence should be interpreted in terms of overall mobility, rather than of specific discipline-to-discipline pathways. More than half of them graduated either in mathematics or engineering, not computer science (see Table 5). The entry point of a scientific career is not in the specialised field, but in some of the underlying knowledge bases, either theoretical or technical. Also interesting is the group of graduate students in physics who are recognized as key leaders in computer science.

Not surprisingly, computer science is number one at the level of Master degrees, a stage in which some focusing is required. Still, it covers only 34.1% of observable cases (including missing observations). Finally, at the PhD stage the disciplinary affiliation of computer science dominates with 38.2% of cases. The large number of missing observations may confound the picture (e.g. do scientists omit this information because it is considered obvious that their PhD is in computer science?).

At the same time an interesting tentative interpretation can be offered. Computer science is a relatively young discipline. It has not the long scientific history of physics, mathematics, or chemistry. Furthermore, it has an intrinsically dual nature: a

Table 5. Distribution of PhD, Master and Bachelor degrees by discipline

	PhD degree		Master degree		Bachelor degree	
	Number	%	Number	%	Number	%
Computer science	327	38.2	156	34.1	102	15.9
Engineering	116	13.6	113	24.7	165	25.7
Mathematics	90	10.5	75	16.4	165	25.7
Physics	25	2.9	14	3.1	45	7.0
Statistics	9	1.1	6	1.3	3	0.5
Psychology	8	0.9	2	0.4	9	1.4
Linguistics, literature	4	0.5	4	0.9		
Economics	2	0.2	6	1.3		
Biology					4	0.6
Chemistry					4	0.6
Other or not specified	274	32.0	81	17.7	144	22.5
Total number of observations	855		457		641	

Table 6. Transition matrix between disciplinary distribution of Bachelor and PhD degrees

Bachelor degree	PhD degree											
	Mathematics		Engineering		Computer science		Other disciplines		No PhD		Total	
	Number	%	Number	%	Number	%	Number	%	Number	%	Number	%
Mathematics	47	8.5	14	49.7	82	11.5	19	11.5	3	1.8	165	100.0
Engineering	4	41.8	69	34.5	57	17.6	29	17.6	6	3.6	165	100.0
Computer science	-	2.0	2	79.4	81	15.7	16	15.7	3	2.9	102	100.0
Total	51	19.7	85	50.9	220	14.8	64	14.8	12	2.8	432	100.0

theoretical discipline, based on advanced research in mathematics, logics, computation, probability, and is also an application-oriented discipline, with a face towards the industrial and commercial feasibility of research results. Our data seem to suggest that computer science has been a gateway for cross-discipline mobility and cognitive recombination.

As a matter of fact, a great deal of cognitive recombination seems to take place within this field. Students may start with a degree in fundamental disciplines (mathematics, physics) and find this new discipline as attractive as old fields for a brilliant career. Engineers do the same. Somewhat less represented, students with a background in human sciences (literature, linguistics, psychology) and social sciences (economics) may combine their domain expertise with advanced computer science.

This interpretation is confirmed by Table 6, which shows the transition matrix between the Bachelor degree and the PhD. The a priori expectation is that there must be consistency between the two, leading to a matrix strongly concentrated along the principal diagonal. This is roughly confirmed for computer science (79.4% on the diagonal cell) but not for mathematics and engineering.

We therefore conclude that computer science is a field characterized by a high degree of disciplinary mobility, attracting competences from related fields. In terms of the search regime framework, this amounts to saying that cognitive complementarity is a key element of the epistemic dynamics.

Again, the European higher education systems are less equipped to deal with this kind of cognitive complementarity. Disciplinary mobility in PhD education, for example, is not encouraged. The European tradition of PhD education is one of subordination to established disciplinary boundaries, rather than of open competition on the basis of research proposals.

The search regime of computer science has been characterized by a turbulent rate of growth, proliferation dynamics, and strong cognitive and institutional complementarity

Patterns of career mobility

Top scientists are scarce and there is competition to attract them. Competition for scarce academic staff of top quality may be considered a layered game: only highly ranked institutions can compete for very top people, and very top people carefully select their appointments in order to increase their opportunities to learn, to have good colleagues and students, to strengthen their CV and to increase their reputation.

Competition, however, is multidimensional. Among people of the same stratum of quality, secondary factors in selecting an affiliation (in addition to personal or family idiosyncratic considerations) include the offer to develop a small but promising research group, or reputation in a niche of the discipline, or the availability of special research facilities, or the like.

We computed the number of career changes in the total sample of scientists. These include any move from assistant professor to associate professor to full professor in different affiliations, or equivalent levels in other academic systems, for academicians, or appointments in different organizations for those working in industry and government. Promotion within the same organization is not considered a career move, even if there is geographical mobility. Geographical mobility at the same level of career (a rare event) is not considered a career move either.

We have 1,010 observations, for which we counted 4,418 career moves, or 4.36 per person. We classified the 4,418 career positions into four classes: academic positions (n = 3,117 or 70.6%), industry positions (n = 786 or 17.8%), consultancy positions (n = 332 or 7.5%) and government positions (n = 183 or 4.1%).

Among many aspects revealed by the analysis of career paths, we particularly note the ranking of academic institutions by the number of career moves that have involved them in the life of top scientists (see Table 7). All top 15 institutions are based in the USA, with the exception of Toronto, which is

Table 7 Ranking of top 15 affiliations (only academic positions) in total number of positions over career

Institution	Number
MIT	174
Stanford University	166
University of California at Berkeley	102
Carnegie Mellon University	102
University of Illinois	59
University of Maryland	58
Cornell University	52
University of Washington	45
University of Pennsylvania	44
Harvard University	44
Princeton University	44
University of Texas	44
University of Massachusetts	42
Brown University	41
University of Toronto	34

Note: universities not in USA are in italics

ranked 15th. We find the data illuminating. It is not surprising that top universities try to attract top scientists, what is impressive is the extreme concentration of this process. The first 15 universities account for 1051 moves, or 33.7% of the total number of academic moves in the entire careers of 1,010 top scientists.

Even more impressive, the first four universities, namely MIT, Stanford, Berkeley and Carnegie Mellon, account for 544 moves, or 17.4% of the total. Assuming only one stop in one of these universities per scientist, we find that almost 54% of all scientists in the sample, coming from all countries in the world, have spent at least a period of their career at just these four universities. Alternatively, assuming multiple career steps within these four universities (admittedly a more realistic scenario) slightly changes the situation: at the extreme, if all average 4.36 moves would have been made in the four universities, we would still find a large group of 136 scientists, spending all their career in only four institutions. Further examination, based on path analysis, can elucidate the pattern better.

For the sake of our discussion, however, what is remarkable is the gravitational pull of highly prestigious universities on the career decisions of top scientists. We find this finding impressive and highly informative in terms of policy implications.

Another interesting finding refers to academia–industry mobility. While we are talking of scientists, whose visibility is measured through citations in publications, we still see quite remarkable mobility within industry positions and between industry and other positions, mainly academia, and vice versa, accounting for 17.8% of the total. Institutional systems that facilitate industry–academia mobility are clearly more attractive for top scientists in this field. Systems like those found in most European countries, where the career boundaries between academia and industry are very rigid, are definitely less attractive.

Duration of career

The analysis of CVs allows us to investigate the length of stay in each position. We limit the analysis to academic careers and investigate four career transitions: from postdoctoral researcher to assistant professor (or researcher in other academic systems, or equivalent), from assistant to associate, from associate to full professor, from full professor to another affiliation in the same level. It should be noted that the number of observations greatly varies across transitions, a limitation that we cannot overcome given the information available.

Let us first examine the postdoctoral transition (see Table 8). At this stage of their career junior scientists are bright, promising researchers, but not yet academic stars. Still their average stay in that position is only 1.8 years ($n = 68$). It seems that the academic system is extremely competent at spotting future scientific leaders. This is in sharp contrast to the well-known phenomenon of the increased average duration of postdoctoral positions in many academic fields, above all life sciences.

Subsequent career moves also follow a fast track: these scientists become associate professors after five years, and full professors after another five years. On the average, they become full professors 12 years after obtaining a PhD, a remarkably fast career indeed. If they finish their PhD at age 22 or 23, they reach the summit in their early 30s.

An easy way to comment these data is to remember that these are star scientists, who have usually produced outstanding contributions in their early years. This comment misses the point. First, precisely because great scientists are extremely productive in their early years, the academic system might obtain many results by postponing the promotions in the career. Second, we are observing average data. Standard deviation informs us that even faster careers are observable. Indeed, for some people promotion to a higher level may occur within a year of the initial promotion!

The dynamics we observe are the result of intense competition among universities to attract the best young researchers, then the best young professors. Without strong competition among universities,

Table 8 Descriptive statistics of duration of stay in academic career positions

Duration of career steps	Number	Min	Max	Mean	Std dev
As postdoctoral researcher	68	0	7	1.81	1.499
As assistant professor	412	0	36	4.89	5.33
As associate professor	336	0	40	5.39	4.175
As full professor	348	0	44	11.51	9.05

career paths would be slower on average. It is because competitors are ready to offer good prospects that all universities, subject to their budget constraints and reputation layer, try to compete. On the other hand, top scientists have large opportunity costs: if they lose opportunities the value they lose is very large, so they will not accept offers that they consider below their opportunity cost. The higher the reputation, the larger the opportunity costs.

In other words, we may think of this career pattern as a dynamic equilibrium, in which all talented scientists are allocated to universities that make best use of their talent, and all universities allocate their budget in the best possible way. If top scientists receive better offers, they move. If universities increase their reputation and have extra budget, they try to improve the quality of their potential candidates. Rapid career opportunities are the outcome of this dynamic.

Patterns of international mobility

Finally, for a subsample of 786 scientists we have been able to track the countries in which they took permanent positions. On average, they moved in 1.35 countries, a remarkable level of international mobility. Taking into account different employment positions, they changed 5.32 times. It was not possible to normalize these data by age or seniority, given several missing items of data. A crude approximation is offered in Table 9, suggesting that on average they may change country for each 30 years of age and each 15 years of professional seniority.

It has been suggested that Europe and the USA differ structurally in the geographic mobility of innovators (Crescenzi *et al*., 2007), insofar as US innovators move more systematically towards cities where opportunities are larger, while Europeans try to develop innovations starting from their existing locations. Our data seem to suggest that in the computer sciences the pattern of geographic mobility has been an ingredient of long-term success.

Table 9. Indicators of international permanent mobility

	Number	Min	Max	Mean	Std dev
Age	173	30	86	56.97	11.585
Number of different countries	786	1	6	1.35	0.686
Number of different employment positions after PhD	786	1	49	5.32	4.376
Number of different country mobility steps per year of age	163	0.01	0.11	0.029	0.017
Number of different country mobility steps per year of seniority	604	0.02	2.00	0.078	0.111

Scientific productivity

We offer a very rough descriptive analysis of the scientific production of top scientists. Admittedly there is room for further research here, which we did not pursue. In particular, the definition of scientific journals and conference proceedings that account for international publications is problematic, so that any external control on the data self-declared in the CVs would require a long and dedicated investigation.

We therefore simply registered the number of self-declared publications, from all categories combined, and carried out a crude comparison with ISI (now Thomson Reuters) sources, by building up a Web of Science count of publications at the end of 2005. These cover only a subset of journals considered important in the computer science community, and do not include many top conferences, that are certainly crucial for scientific careers.

With all these caveats, it appears that on average top scientists self-declare almost 90 publications. Taking into account the age distribution, so that many individuals in the top list are still in their 30s, is a remarkable figure.

Other useful information can be obtained from Table 10. One-fifth of the top scientists also actively produce complete software and mention it in their CVs. In this case, on average four programs are mentioned. In addition, 137 scientists mention patents in their CV, with an average number of 6.57. Thus top scientists are also active producers of non-publication research output. This confirms the notion that institutional complementarity is an integral part of the search regime in computer science.

Discussion of findings and policy implications

The hidden dimension of industrial competitiveness, or why Europe lags behind

Prevailing explanations of the European competitiveness gap in the IT industry, as already discussed, are based on the lack of government initiative, small

Table 10. Selected indicators of research output

	Number of observations	Min	Max	Mean	Std dev
Publications					
Number of publications mentioned in CV	903	1	964	87.74	95.58
Number of ISI international papers	983	1	284	24.73	34.59
Other research output					
Software	204	1	56	4.14	6.081
Patents	137	1	47	6.57	8.342

Despite the widely held assumption that Europe is good at science but poor at technology transfer (the so-called European paradox), it is the weakness in its scientific base that is responsible for its poor industrial performance

market size, internal market fragmentation, and deep separation between the military sector and civilian research.

We suggest a complementary line of explanation. For a large industry such as the computer industry, an overall ecology of abstract ideas, engineering capabilities, technical skills, and entrepreneurial visions, is needed. This ecology is nurtured by the interaction between universities and companies, and between companies and large (public and private) customers. On the side of industry, what is crucial is the working of mechanisms that also permit large-scale experimentation, massively bottom-up parallel efforts, together with powerful selection mechanisms to foster the scaling up and growth of successful ideas. Universities can contribute to this ecology in two main ways: by producing top class research and education, and by pushing entrepreneurial efforts of researchers to the market. European countries largely failed in both these directions. Contrary to the widely held assumption that Europe is good in science but poor in technology transfer (the so-called European paradox) we suggest that it is the weakness in the scientific base that is responsible, indirectly and in the long run, but in a powerful way, for the poor industrial performance.

Implications for higher education policy

The interesting question is now whether this search regime has been compatible with the institutional features of European higher education in the relevant historical period, and why. The answer is negative. A search regime characterized by a turbulent rate of growth, proliferation, and strong cognitive and institutional complementarity requires an institutional system that favours career mobility, competition based on peer review, a competitive PhD education system, cross-disciplinary mobility and industry–academia mobility (Bonaccorsi, 2011). According to our data, top scientists move from the university that awarded their Bachelor degree to the USA, fight to enter top class universities as students, change affiliations several times in their career, combine different disciplines around computer science, enjoy a rapid career, have extensive industry involvement, as witnessed by research collaborations, as well as software development and patents.

Computer science has been based on a fierce competition for students and researchers worldwide. Knowing how severe these demands are, top class universities fight to attract the best students and try to offer the best conditions to professors. But European universities have not been attractive for top computer scientists and increasingly have also become less attractive for students. Among well-reputed old European universities, just a few have international visibility at the top.

These findings support the importance of fostering the reform agenda for European universities. This will require dedicated efforts to build up globally competitive PhD programs, more transparent and competitive recruitment procedures for researchers, larger mobility of researchers. The creation of the European Research Council has been an important step in this direction, but more is needed. The situation is rapidly changing, with these issues on top of the reform agenda in many European countries. However, there is also very recent evidence that the type of brain race that we have discovered in the computer science is becoming widespread (Wildavsky, 2010). This will continue to put pressure on European higher education systems in the near future.

Implications for innovation policy

In the relevant historical period most European countries did not have (and many still do not have) the institutional features to support the IT innovation ecology. Governments considered the computer industry a sector that could be supported with the old model of industrial policy: a sort of command-and-control attitude, coupled with large financial support to national champions. They did not create the legal, administrative and financial conditions for large-scale entrepreneurial activity in high technology.

In historical terms, the innovation policies of large European countries have been largely influenced by the notion of national champions (Laredo and Mustar, 2001). A case in point was the French industrial policy towards the IT industry, which culminated in the Plan Calcul. As stated by Mounier-Kuhn (1994: 209):

> The Plan Calcul, one of the most ambitious technological programmes of the Fifth Republic, aimed at establishing an informatics industry that would guarantee France independence from the American manufacturers. The government's policy was to shape a 'national champion', a company, preferably big (if necessary, formed by 'inducing' several companies to merge) which the state would support through R&D grants and preferential purchases.

Although with less emphasis, these ideas have been shared by most governments for decades.

The search regime framework offers an explanation for such policy failures. As we have demonstrated, the competitiveness of the IT industry depends on ongoing, although complex and nonlinear, relations between industry and the academic environment. The search regime in computer science is based on a massive and fast effort of exploration of many competing directions, which are *ex-ante* extremely uncertain and risky. No centralized system, either in science and technology, could cope with such a regime.

The main tool for the transformation of ideas into commercial innovations has been the creation and rapid growth of start-up companies. They constitute the industrial counterpart of a turbulent and proliferating search regime in science. It must be said that within a broad historical perspective, as the literature examined above clearly shows, the entrepreneurial process of creating new firms from research in the IT industry started very early in the USA, in the 1950s and 1960s. The firms created in these periods had to survive in a harsh competitive environment, to access the risk capital market and eventually the stock exchange market, and to discover the recipe to combine cutting edge technology with manufacturing and marketing skills. When the two radical innovations of the PC (in the 1980s) and the internet (in the 1990s) were introduced, the US system already had several decades of trial-and-error, failures and institutional learning on which it was possible to capitalize. The entrepreneurial process started much later in Europe, partly because of the lack of competition, partly because of the poor ecology of ideas.

Luckily enough, the recognition of the importance of young innovative firms in the industrial dynamics has been reached quite late in European innovation policy, but is now firmly established in the policy debate. The recent *EU Industrial R&D Investment Scoreboard* states clearly that:

> …the EU's innovation gap is a consequence of its industrial structure in which new firms fail to play a significant role in the dynamics of the industry, especially in the high-tech sectors. (European Commission, 2010: 51)

Our findings confirm quite neatly the need for a shift of policy focus, from merely supporting industrial research, perhaps with large involvement of large (but not globally competitive) European firms, to the creation of framework conditions for rapid growth of young innovative firms.

Implications for productivity and the role of services

There is a large policy debate in Europe on the causes of the growth deficit with respect to the USA. There is also agreement on the role of a large productivity gap in the service sector, as demonstrated by the Brookings Institution (Triplett and Bosworth, 2004) and recently by the KLEMS project (Timmer *et al*., 2010). When we come to the explanation of the productivity gap in the service sector, one commonly held view is that regulation plays a key role. Following the influential analysis by the OECD (Nicoletti and Scarpetta, 2003; Conway and Nicoletti, 2006) it has been suggested that strict product market regulations and lack of regulatory reforms underlie the poor productivity of some European countries, particularly in ICT-related sectors. Strictly associated with product market regulation, labour market regulation is called into play, as flexible labour markets in the USA facilitate the redeployment of the workforce and then the adoption of innovation much more than in Europe.

We suggest a complementary interpretation, but one which reverses the causal path. It is because the service sector in the USA started to experiment with IT very early, in the 1960s and 1970s, that it adopted IT on a large scale in the 1990s. In turn, it was because IT immediately deployed large gains in the efficiency of operations that a steady increase in productivity was made compatible with acceptable work conditions in an advanced society, without strong political opposition to liberal reforms. In fact, in the service sector the productivity may increase either because a process of automation is implemented in the back office, or because there is an intensification of effort in the front office. The former invariably requires skillful implementation of IT, while the latter may be obtained by increasing the working hours or the physical effort of workers and/or by lowering real wages. There is historical evidence from the literature discussed in this paper, that US companies in the IT industry started to work with large service firms as potential customers as early as the 1960s. While the most famous developments refer to the airline reservation system (the SABRE project developed in the period 1957–1964), there are many other less known examples in the banking, insurance, wholesale, retail, transport or logistics industries. Why are these early experiences historically important? The reason lies again in the kind of institutional complementarity we find in this search regime: problems created by challenging requirements in the user sector generate a feedback on the creation of new ideas, and new ideas need a long period of incubation, adaptation and implementation in companies to deliver their full potential over productivity. In turn, the deployment of new technology in services is intertwined with organizational changes, and only the combination between these two dimensions delivers large productivity gains (Brynjolfsson and Hitt, 2000).

Our conjecture (admittedly, only that) is that US service companies were ready to jump on the new waves of IT associated to the PC and the internet exactly because they had already experienced the early benefits of the technology, while for European service companies the learning curve, in the same period, was much less favourable. Consistent with this conjecture is the robust finding that US multinationals exhibit systematically higher productivity level than European ones (Bloom *et al*., 2007). If this conjecture were to be confirmed, then the policy implication would be somewhat less simplistic than just placing more flexibility in the labour market.

Notes

1. The EU Report includes STMicroelectronics as incorporated in Switzerland, with an R&D expenditure of €1.065 billion. The company is, in fact, also owned by public shareholders from Italy and France. In the *2010 Scoreboard* it is registered as incorporated in Netherlands.
2. CiteSeer was developed in 1997 at the NEC Research Institute, Princeton, NJ. The service then moved to the College of Information Sciences and Technology, Pennsylvania State University in 2003. The CiteSeer service has since been replaced by the 'new generation' or CiteSeerX, with collaboration from several universities worldwide. It is currently available at <http://citeseerx.ist.psu.edu/>, last accessed 13 July 2011.

References

Alic, J A, L M Branscomb, H Brooks, A B Carter and G L Epstein 1992. *Beyond Spinoff. Military and Commercial Technologies in a Changing World.* Boston, MA: Harvard Business School Press.

Bassett, R K 2002. *To the Digital Age. Research Labs, Start-up Companies, and the Rise of MOS Technology*. Baltimore, MD: Johns Hopkins University Press.

Bauer, F L 2002. A computer pioneer's talk: pioneering work in software during the 50s in Central Europe. In *History of Computing: Software Issues*, U Hashagen, R Keil-Slawik and A L Norberg (eds.). Berlin: Springer.

Becchetti, L 2001. The determinants of suboptimal technological development in the system company–component producers' relationship. *International Journal of Industrial Organisation*, **19**(9), 1407–1421.

Bloom, N, R Sadun and J Van Reenen 2007. Americans do I.T. better: US multinationals and the productivity miracle. Centre for Economic Performance, Working Paper. London: London School of Economics and Political Science.

Bonaccorsi, A 2007. On the poor performance of European science: institutions vs policies. *Science and Public Policy*, **34**(5), 303–316.

Bonaccorsi, A 2008. Search regimes and the industrial dynamics of science. *Minerva*, **46**(3), 285–315.

Bonaccorsi, A 2010. New forms of complementarity in science. *Minerva*, **48**(4), 355–387.

Bonaccorsi, A 2011. Institutions of science and fast moving scientific fields. In *The Changing Governance of Research*, D Jensen (ed.). New York: Springer.

Bonaccorsi, A and J Vargas 2010. Proliferation dynamics in new sciences. *Research Policy*, **39**(8), 1034–1050.

Books LLC 2010a. *Computer Designers*. Memphis, TN: Books LLC (extracts from Wikipedia).

Books LLC 2010b. *German Computer Scientists*. Memphis, TN: Books LLC (extracts from Wikipedia).

Bresnahan, T F and M Trajtenberg 1995. General purpose technologies. engines of growth. *Journal of Econometrics*, **65**(1), 83–108.

Brynjolfsson, E and L Hitt 2000. Beyond computation: information technology, organizational transformation, and business performance. *Journal of Economic Perspectives*, **14**(4), 23–48.

Campbell-Kelly, M 1989. *ICL. A Business and Technical History. The Official History of Britain's Leading Information Systems Company*. Oxford, UK: Clarendon Press.

Campbell-Kelly, M 2003. *From Airline Reservations to Sonic the Hedgehog. A History of the Software Industry.* Cambridge, MA: MIT Press.

Campbell-Kelly, M and W Aspray 2004. *Computer. A History of the Information Machine*. Cambridge, MA: Westview Press.

Cantwell, J and G D Santangelo 2003. The new geography of corporate research in Information and Communications Technology (ICT). In *Change, Transformation and Development*, J S Metcalf and U Cantner (eds.). Heidelberg, Geremany: Physica-Verlag.

Casper, S, M Lehrer and D Soskice 1999. Can high-technology industries prosper in Germany? Institutional frameworks and the evolution of the German software and biotechnology industries. *Industry and Innovation*, **6**(1), 5–24. Also in Bob Hanckè (ed.) 2009. *Debating Varieties of Capitalism*. Oxford, UK: Oxford University Press.

Ceruzzi, P E 1998. *A History of Modern Computing*. Cambridge, MA: MIT Press (2nd edition, 2003).

Chandler, A 1990. *Scale and Scope: The Dynamics of Industrial Capitalism.* Cambridge, MA: Harvard University Press.

Colmerauer, A and P Roussel 1996. The birth of Prolog. In *History of Programming Languages- II*, T J Bergin and R G Gibson (eds.). New York: Addison-Wesley.

Conway, P and G Nicoletti 2006. Product market regulation in the non-manufacturing sectors of OECD countries: Measurement and highlights, OECD Economics Department Working Paper 530. Paris: OECD

Copeland, J P *et al*. (eds.) 2006. *Colossus. The Secrets of Bletchley Park's Codebreaking Computers*. Oxford, UK: Oxford University Press.

Crescenzi, R, A Rodriguez-Pose and M Storper 2007. The territorial dynamics of innovation: a Europe–United States comparative analysis. *Journal of Economic Geography*, **7**(6), 673–709.

Dalum, B, C Freeman, R Simonetti, N von Tunzelmann and B Verspagen 1999. Europe and the information and communication technologies revolution. In *The Economic Challenge for Europe*, J Fagerberg, P Guerrieri and B Verspagen (eds.). Cheltenham, UK: Edward Elgar.

Davis, M 2000. *Engines of Logic. Mathematicians and the Origin of the Computer.* New York, Norton and Company.

Dummer, G W A 1997. *Electronic Inventions and Discoveries. Electronics from its Earliest Beginnings to the Present Day.* Bristol, UK: Institute of Physics Publishing.

European Commission 2005. *Monitoring Industrial Research. The 2005 EU Industrial R&D Investment Scoreboard. Volume II: Company Data*. Brussels: Directorate-General Joint Research Centre.

European Commission 2007. *Towards a European Research Area. Science technology and innovation Key Figures 2007.* Luxembourg: Office for Official Publications of the European Communities.

European Commission 2008. *A More Research-intensive and Integrated European Research Area. Science, Technology and Competitiveness Key Figures Report 2008/2009*. Luxembourg: Office for Official Publications of the European Communities.

European Commission 2010. *Monitoring Industrial Research. The 2010 EU Industrial R&D Investment Scoreboard.* Brussels: Directorate-General Joint Research Centre.

Flamm, K 1988. *Creating the Computer: Government, Industry and High Technology*. Washington, DC: Brookings Institution.

Freiberger, P and M Swaine 1984. *Fire in the Valley. The Making of the Personal Computer*. New York, McGraw Hill.

Hultèn, S and B Mölleryd 2003. Entrepreneurs, innovations and market processes in the evolution of the Swedish mobile telecommunications industry. In *Change, Transformation and Development*, J S Metcalfe and U Cantner (eds.). Heidelberg, Germany: Physica-Verlag.

Inklaar, R, M O'Mahony and M Timmer 2003. ICT and Europe's productivity performance: Industry-level growth account comparisons with the United States, Research Memorandum GD-68. Groningen, The Netherlands: Growth and Development Centre, University of Groningen.

Jorgenson, D W and K J Stiroh 2000. Raising the speed limit: U.S. economic growth in the Information age. *Brookings Papers on Economic Activity*, **1**, 125–211.

Kargon, R, S Leslie and E Schoenberger 1992. Far beyond big science: Science regions and the organization of research and development. In *Big Science*. *The Growth of Large-Scale Research*, P Galison and B Hevly (eds.). Stanford, CA: Stanford University Press.

Langlois, R 1992. External economies and economic progress. The case of microcomputer industry. *Business History Review*, **66**, 1–50.

Langlois, R and P Steinmuller 1999. The evolution of competitive advantage in the worldwide semiconductor industry, 1947–1996. In *Sources of Industrial Leadership. Studies of Seven*

Industries, D Mowery and R R Nelson (eds.). Cambridge, UK: Cambridge University Press.

Larédo, P and P Mustar 2001. French research and innovation policy: Two decades of transformation. In *Research and Innovation Policies in the New Global Economy. An International Comparative Analysis*, P Larédo and P Mustar (eds.). Cheltenham, UK: Edward Elgar.

Lavington, S 1980a. *Early British Computers*. Manchester, UK: Manchester University Press.

Lavington, S 1980b. Computer development at Manchester University. In *A History of Computing in the Twentieth Century. A Collection of Essays*, N Metropolis, J Howlett and G Rota (eds.). New York: Academic Press.

Leclerc, B 1990. From Gamma 2 to Gamma E.T.: The birth of electronic computing at Bull. *Annals of the History of Computing*, **12**(1), 5–22.

Lécuyer, C 2006. *Making Silicon Valley. Innovation and the Growth of High Tech, 1930–1970.* Cambridge, MA: MIT Press.

Leslie, S 1992. *The Cold War and American Science: The Military–Industrial Academic Complex at MIT and Stanford.* New York: Columbia University Press.

Leslie, S and R Kargon 1996. Selling Silicon Valley: Frederick Terman's model for regional advantage. *Business History Review*, **70**(4), 435–472.

Levy, S 1984. *Hackers. Heroes of the Computer Revolution*. New York, Doubleday.

Lowen, R 1997. *Creating the Cold War University. The Transformation of Stanford*. Berkeley, CA: University of California Press.

Mamuneas, T P 1999. Spillovers from publicly financed R&D capital in high tech industries. *International Journal of Industrial Organization*, **17**(2), 215–239.

Moreau, R 1984. *The Computer Comes of Age. The People, the Hardware, and the Software.* Cambridge, MA: MIT Press.

Mounier-Kuhn, P E 1994. French computer manufacturers and the component industry, 1952–1972. *History and Technology*, **11**(2), 195–216.

Mowery, D (ed.) 1996. *The International Computer Software Industry*. Oxford, UK: Oxford University Press.

Mowery, D C and N Rosenberg 1998. *Paths of Innovation. Technological Change in 20th Century America.* Cambridge, UK: Cambridge University Press.

National Research Council 2004. *Computer Science. Reflections on the Field, Reflections from the Field.* Washington, DC: National Academies Press.

Nicoletti, G and S Scarpetta 2003. Regulation, productivity and growth: OECD evidence. *Economic Policy*, **18**(36), 9–72

Norberg, A L 2005. *Computers and Commerce. A Study of Technology and Management at Eckert-Mauchly Computer Company, Engineering Research Associates, and Remington Rand, 1946–1957*. Cambridge, MA: MIT Press.

Norberg, A L and J E O'Neill 1996. *Transforming Computer Technology. Information Processing for the Pentagon, 1962–1986.* Baltimore, MD: Johns Hopkins University Press.

O'Mahony, M and M P Timmer 2009. Output, input and productivity measures at the industry level: the EU KLEMS database. *Economic Journal*, **119** (June), F374–F403.

O'Mahony, M and M Vecchi 2005. Quantifying the impact of ICT capital on output growth: A heterogeneous dynamic panel approach. *Economica*, **72**(No 288), 615–633.

Peterson, L and D Clark 2004. The internet: an experiment that escaped from the lab. In *Computer Science. Reflections on the Field, Reflections from the Field*, National Research Council (ed.), pp 129–133. Washington, DC: National Academies Press.

Pugh, E 1984. *Memories that Shaped an industry: Decisions leading to IBM System/360*. Cambridge, MA: MIT Press.

Pugh, E 1995. *Building IBM: Shaping an Industry and its Technology*. Cambridge, MA: MIT Press.

Randell, B 1980. The COLOSSUS. In *A History of Computing in the Twentieth Century. A Collection of Essays*, N Metropolis, J Howlett and G Rota (eds.). New York, Academic Press.

Rojas, R 2006. The architecture of Konrad Zuse's early computing machines. In *The First Computers. History and Architectures*, R Rojas and U Hashagen (eds.). Cambridge, MA: MIT Press.

Santangelo, G D 1998. Corporate technological specialisation in the European information and communication technology industry. *International Journal of Innovation Management*, **2**(3), 339–366.

Shaw, M 2004. Strategies for software engineering research. In *Computer Science. Reflections on the Field, Reflections from the Field*, National Research Council (ed.), pp 151–158. Washington, DC: National Academies Press.

Stroustrup, B 1996. A history of C++: 1979–1991. In *History of Programming Languages- II*, T J Bergin and R G Gibson (eds.). New York: Addison-Wesley.

Swedin, E G and D L Ferro 2005. *Computers. The Life Story of a Technology*. Westport, CT: Greenwood Press.

Ten Raa, T and E N Wolff 2000. Engines of growth in the US economy. *Structural Change and Economic Dynamics*, **11**(4), 473–489.

Timmer, M P and B van Ark 2005. Does information and communication technology drive EU–US productivity growth differentials? *Oxford Economic Papers*, **57**(4), 693–716.

Timmer, M P, R Inklaar, M O'Mahony and P van Ark 2010. *Economic Growth in Europe: A Comparative Industry Perspective.* Cambridge, UK: Cambridge University Press.

Triplett, J E and B P Bosworth 2004. *Productivity in the US Services Sector. New Sources of Economic Growth.* Washington, DC: Brookings Institution.

Van Ark, P, M O'Mahony and M P Timmer 2008. The productivity gap between Europe and the United States: trends and causes. *Journal of Economic Perspectives*, **22**(1), 25–44.

Van Reenen, J and N Bloom 2007. Measuring and explaining management practices across firms and countries. *Quarterly Journal of Economics*, **122**(4), 1351–1408.

Watson, T Jr 1990. *Father, Son & Co.: My life at IBM and Beyond.* New York: Bantam.

Wildavsky, B 2010. *The Great Brain Race. How Global Universities are Reshaping the World.* Princeton, NJ: Princeton University Press.

Wildes, K L and N A Lindgren 1985. *A Century of Electrical Engineering and Computer Science at MIT, 1882–1982.* Cambridge, MA: MIT Press

Williams, M R 2000 A preview of things to come: Some remarks on the first generation of computers. In *The First Computers. History and Architectures*, R Rojas and U Hashagen (eds.). Cambridge, MA: MIT Press.

Wirth, N 1996. Recollections about the development of Pascal. In *History of Programming Languages- II*, T J Bergin and R G Gibson (eds.). New York, Addison-Wesley.

Zemanek, H 1997. Hardware–software. An equivalence and a contradiction. In *Foundations of Computer Science. Potential-Theory- Cognition*, C Freksa, M Jantzen and R Valk (eds.). Berlin: Springer.

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