Knowledge patterns and sources of leadership: mapping the semiconductor miniaturization trajectory

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Abstract

This paper aims at exploring the sources of leadership in the semiconductor industry by mapping the pattern of knowledge advancement that pushed the miniaturization trajectory and the national organizations that generated it. To this purpose, we build a USPTO database of patents granted between 1976 and 2008 for the miniaturization trajectory and analyze it through four algorithms for the analysis of citation networks. The results reveal the core discoveries, the main streams of growth, and the major clusters of inventions of the miniaturization trajectory. By analyzing the geographical and organizational distribution of the knowledge pattern, we disclose the relative capabilities of national organizations in generating new knowledge along the miniaturization trajectory and discuss the factors that shaped them. We found that the scale and the pattern of domestic demand have been an important source of leadership, but proved to have long-lasting effects when coupled with broad and high-quality "knowledge infrastructures" generated by public and scientific organizations.

Keywords: Technological knowledge, Semiconductor miniaturization trajectory, Citation network analysis, Sources of leadership.

1. Introduction

In the last six decades, the worldwide evolution of technology and industrial leadership has been powerfully influenced by the growth of the semiconductor industry because of the pervasive and general-purpose nature of its technologies.

The emergence of semiconductors in the US during the 1950s assured the country an uncontested leadership, which in the 1980s was challenged by the strength of Japanese business groups. In the 1990s, the American resurgence and the rise of SEA countries quickly changed the scenario of the previous decade, while the relatively peripheral role played by European countries has remained basically unchanged during the whole history of the industry. The factors behind this pattern of industrial leadership have been at the centre of a long debate. The main explanations have focused on the scale and pattern of domestic demand, the industrial strategy and structure, governments' policies, and a number of national/regional/sectoral institutions, including the financial system, the labour market, and the university system[1].

In high-technology industries, industrial leadership largely depends on technological leadership and the relative capabilities of national organizations in generating new knowledge. This paper aims at exploring the sources of leadership in the semiconductor industry by mapping the pattern of knowledge advancement that pushed the miniaturization trajectory and the national organizations that generated it. The studies on technological paradigms and trajectories (Dosi 1982, 1984) highlighted that semiconductors emerged as a result of the generation and accumulation of radically new knowledge around the need for increasing miniaturization of electronic components. Along this process, three basic innovations (the transistor, the integrated circuit and the microprocessor) emerged as answer to the miniaturization imperative and a collective cognitive frame was defined through the creation of specific knowledge bases and pattern of inquire shared by the community of practitioners. However, the realization of the "promise" contained in such basic innovations, and in the technological paradigm itself, crucially depended on the continuous and incremental accumulation of new knowledge along the miniaturization trajectory. Such dynamics, which can be observed ex-post in the space of the semiconductor products characteristics, has driven the whole semiconductor evolution, advancing for more than 50 years according to a strikingly stable rate, i.e. the Moore's law.

We take as a unit of analysis the miniaturization trajectory. Firstly, we trace the pattern of knowledge advancement underlying the last 30-year evolution of the miniaturization trajectory by identifying its core discoveries, main streams of growth, and major clusters of inventions. To this purpose, we build an USPTO database of patents granted between 1976 and 2008 for the miniaturization trajectory and investigated it through a number of techniques which combine quantitative and qualitative methods. Based on the Hummon and Doreian (1989) analysis of citation networks, such techniques have been recently proposed for mapping the technological trajectories that have characterized the evolution of specific fields (Mina et al. 2007, Verspagen 2007, Fontana et al. 2009). Secondly, we analyze the geographical and organizational distribution of the pattern of knowledge advancement, disclosing the relative capabilities of national organizations in generating new knowledge along the miniaturization trajectory and discussing the factors that shaped them. The rest of the paper is organized as follow. Section 2 is an overview of the history of the miniaturization trajectory, with a focus on the most recent technological challenges. Section 3 presents the data and the methodology. Section 4 illustrates and analyzes the pattern of knowledge advancement. Section 5 discusses the pattern and the sources of leadership revealed by the network analysis of patent citations, and section 6 concludes.

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[1] See among the others: Tilton (1971), Braun and MacDonald (1982), Dosi (1984), Malerba (1985), Aoky (1990), Florida and Kenney (1990), Callon (1995), Chen and Swell (1996), Hong (1997), Mathews (1997), Lynn (2000), Langlois and Steinmueller (1999), Tung (2001).

2. The miniaturization trajectory

The miniaturization trajectory refers to the continuous scaling down of the minimum sizes of electronic components in order to allow the integration of an ever-increasing number of additional functionalities on the same integrated circuit. Fig. 1 shows the evolution of the miniaturization trajectory in the last 40 years. As semiconductor process technology advancements allowed to scale down[2], the number of transistors that could be integrated on the same chip increased according to the Moore's Law, which states that number of components per chip increases exponentially, doubling roughly every 24 months (Moore 1965). This enabled the realization of ever more complex semiconductor devices along the technological eras that have characterized the evolution of the miniaturization trajectory.

A decade after the invention of the transistor, the IC integrated a whole electronic circuit on a single silicon substrate leading to enormous performance increase and cost reduction compared with the manual assembly of circuits using discrete components. During the small-scale integration (SSI) era, in the early 1960s, a chip contained just a few tens of transistors, which became few hundreds in the late 1960s, during the medium-scale integration (MSI) era. The large-scale integration (LSI) era allowed the emergence of the first microprocessor (the Intel 4004) and the first DRAM memory (the 1K Intel). The microprocessor was a fundamental breakthrough in the semiconductor history, since the integration of a whole processor (CPU[3]) on a single IC containing the equivalent of thousands discrete transistors, allowed huge cost reduction and processing speed increase. The first commercially available microprocessor was built by Intel in the early 1970s. Intel never applied for a patent covering the microprocessor and finally the first microprocessor patent was granted to Texas Instruments in 1973. The very large-scale integration (VLSI) era offered microprocessors and memories containing well over a million transistors on a single piece of silicon. The management of the growing complexity of VLSI chips was enabled by the development in the 1980s of computerized design tools[4], which evolved in the modern EDA tools and allow engineers to test ICs functional performances before their manufacture. In the mid-1990s, the advancement of the semiconductor process technology had pushed the miniaturization trajectory to 350-250 nm, allowing the realization of SoCs, which integrate a whole electronic system (e.g. a computer) on a single chip, with both hardware and software embedded (Martin 2003:1)[5].

Insert Fig.1 about here

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[2] This is the process technology whereby semiconductor chips are manufactured. Transistor dimensions are measured in microns (μm). A micron is one millionth of a metre. Therefore it is possible to refer to, for example, a 0.5 μm IC or say that an IC is built with a 0.5 μm process, meaning that the smallest transistors are 0.5 μm in length. Since the 1990s, it has become a common practice to use the nanometre (nm) unit. A nanometre is one billionth of a metre.

[3] A CPU is the fundamental component of computers of any era because its ability of executing a program gives computers the essential feature of programmability.

[4] Prior to the 1980s chips were largely designed by hand.

[5] By definition, an SoC incorporates at least one or more processors, memory blocks, an Input/Output interface, and an interconnection between these three components. One of the first examples of SoCs were second generation cellular phones.

The miniaturization trajectory influenced as well the other major directions of change of semiconductor technology, i.e. decreasing cost-per-function and power consumption, increasing processing speed, compactness, and functionality. Indeed, as sizes shrink, costs per chip decrease, processing speed increases, power consumption is reduced, and final electronic products become more compact and multifunction.

The impressive increase of ICs complexity that enabled SoCs, created an important discontinuity in electronics design, but also demanded the invention of new design methodologies in order to handle such complexity (Chang et al. 1999). Although in the last years many efforts have been devoted to this task, a considerable lack of pragmatic knowledge remains among practitioners regarding the leading methodologies for the SoC design (Martin and Chang 2003: xii). This is the source of an ever-widening "design productivity gap", which is considered one of the most severe challenges for the continuous growth of the semiconductor industry: while ICs complexity and density has increased rapidly following the Moore's Law, improvements in the productivity of IC designers have failed to keep up (Linden and Somaya 2003:548).

Different solutions have been discussed to face these design challenges. In the second half of the 1990s, it was proposed the use of the IP (Intellectual Property) based design and the IP reuse, where pre-designed and pre-verified IP blocks are internally manufactured or licensed from third-parties. IP blocks can be embedded memories, processors, communication links, etc., having a self-contained designed functionality. The SoC designer, who would have only limited knowledge of the internal structure of these blocks, could combine them into a chip to implement complex functions, and reuse them in all chips that require those specific functionalities. More recently, the IP based design has been followed by the development of the platform-based design, which is one of the approaches to the heavy IP reuse based design of SoCs. Rather than looking at IP reuse in a block-by-block manner, platform based design aggregates groups of components into reusable platform architectures (Martin 2003:12). Other recent research directions addressing the SoC design challenges are the Network-on-a-Chips (NoCs) and the Programmable SoCs (PSoCs). The NoC approach is based on the application to the SoC design of the models from the network design field and focuses on the development of advanced interconnect technologies for interconnecting SoC components (Benini and De Micheli 2002:71). With increasing time-to-market pressures, programmable logic devices (PLDs) have been increasingly merged into SOCs, allowing the realization of PSoCs, which represent a particularly exciting and intriguing combination of in-filed flexibility and programmability (Martin and Chang 2003: xiii). PDLs are electronic components characterized by high degrees of flexibility since they can be configured by the customer or designer after manufacturing. This feature and the consequently low sunk costs of production make PDLs suitable for many applications. PSoCs are SoCs that incorporate one or more programmable logic cores.

3. Data and methodology

The methodology developed in this study is based on an interactive process involving industry studies, practitioners' accounts and the network analysis of patent citations. After studying the literature on the semiconductor industry and technology, we interviewed a number of practitioners, from both academia and enterprises. With this background we built the database of patent citations and analyzed it through four network analysis algorithms. Then we came back to the literature and practitioners' accounts for interpreting the relevant results.

Since the work of Garfield et al. (1964), citations among papers have been increasingly used in network analysis studies to trace the pattern of scientific advancement. An important contribution in this direction was given by Hummon and Doreian (1989), who proposed three indices for the identification of the most important streams of growth of a scientific field, i.e. the main path analysis. In the last years, network analysis has greatly benefited from the development of network analysis algorithms originating from the field of the graph theory. In particular, Batagelj (2003) showed how to efficiently compute the Hummon and Doreian's indices so that they can be used also for analysis of large citation networks.

Citations among patents have been commonly used in the studies on innovation and technological change for weighting the importance of individual patents by counting the number of citations received (Grilices 1990, Jaffe and Trajtenberg 2002). However, this approach is not useful when the focus is on the evolution of technological knowledge in a specific field. More recently, a number of studies have extended the Hummon and Doreian's techniques to the analysis of citations among patents for mapping the technological trajectories that have characterized the evolution of specific fields (Mina et al. 2007, Verspagen 2007, Fontana et al. 2009). In this paper, we use and extend the methodology proposed by Mina et al. (2007) and Batagelj (2003) for tracing the pattern of knowledge advancement underlying the evolution of the miniaturization trajectory. In this context, patents concerning the miniaturization trajectory correspond to the vertices of the network and are connected with each other by a number of arcs, which symbolize the citational links among patents. Each patent represents a discrete piece of technological knowledge that has passed the scrutiny of trained specialists and has been granted on the basis of relatively objective standards. Since it is a legal duty for the assignee of a patent to disclose the existing knowledge, each citation represents a previously existing piece of knowledge that has been incorporated and further developed by the patent. Citations among patents, making explicit the epistemic links among the pieces of knowledge from which the miniaturization trajectory emerged, can be used to identify its pattern of knowledge advancement.

First, we built a patent database for the miniaturization trajectory, which was extracted from the USPTO (United States Patent and Trademark Office)[6] by means of a key-words search on titles, abstracts and claims of patents granted from 1976 to 2008. The key-words strategy was selected by consulting a broad range of

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[6] The USPTO database is freely available at www.uspto.gov/

secondary sources and interviewing a number of experts[7]. The final database contains 41,787 patents and 121,393 citations among patents. We then constructed a series of maps that allow us to trace, visualise, and discuss the pattern of knowledge advancement that pushed the miniaturization trajectory in the last 30 years. Maps were built by applying to our citations network four algorithms implemented by Pajek, a program for the analysis and visualization of large networks[8].

The first algorithm is the main subnetwork and shows the time evolution of the citation network, drawing the pattern of convergence or divergence over time of the main solutions proposed by practitioners to solve the challenges stemming from the advancement of the miniaturization process. In doing that, this algorithm maps the main streams of growth of the miniaturization trajectory. Following Batagelj (2003), we calculated traversal weights on arcs through the Search Path Count (SPC) method, deleting all arcs with weights lower than a selected threshold and all isolated vertices. By organizing the network in layers corresponding to patents ordered by time, we obtained the main subnetwork.

The second algorithm is the Critical Path Method (CPM) and selects, among the main streams of growth mapped by the main subnetwork, the most vital one, thus identifying the technical solutions that turned out to be successful at the end of the period considered (2008). The main alternative to the CPM is the Main Path algorithm. Once calculated traversal weights of citations through the SPC method, the CPM determines the path from an entry vertex to an exit vertex with the largest total sum of weights on its arcs, while the Main Path calculates the path from an entry vertex to an exit vertex with the highest weights on its arcs. As showed in Batagelj (2003), the CPM captures the most vital stream of knowledge accumulation.

The third algorithm is called Island and identifies the main clusters of inventions in the entire research space of the miniaturization trajectory. Clusters represent the major specialized bodies of technological knowledge that contributed to the advancement of the miniaturization trajectory and that over time benefited from the realization of miniaturized semiconductor components. This algorithm has been recently developed by Batagelj and Zaversnik (2004) and is part of the main path analysis since it is based on the calculation of SPC traversal weights on arcs. However, here traversal weights are used to identify non-overlapping subsets of vertices that, according to the arc weights, are more closely connected with each other than with external vertices. As demonstrated in Batagelj et al. (2006), each subnetwork identified by the Island algorithm has the same topic, therefore Islands can be viewed as thematic clusters. In order to investigate those areas of inquiry of the miniaturization trajectory that emerged in the last few years, we applied the Island algorithm even to a reduced database starting from 2000.

Finally, the Hubs and Authorities algorithm selects the core knowledge contributions that laid the foundations of the miniaturization trajectory (Authoritative patents), and the patents that best developed such

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[7] Two professors of electronics engineering from the Politecnico of Milan and one engineer from the STMicroelectronics of Agrate Brianza were interviewed on both the key-words strategy and the most important technological developments of the miniaturization trajectory.

[8] Pajek is freely available at http://pajek.imfm.si/doku.php?id=download.

contributions (Hub patents). Hubs and Authorities are formal notions of structural prominence of vertices (Brandes and Willhalm 2002:1). Therefore, differently from the main path analysis, which identifies the most important streams of growth in a citation network, the Hubs and Authorities algorithm focuses on the structure of a citation network, determining its most important vertices. The concept at the basis of this algorithm can be dated back to Pinski and Narin (1976), who proposed to measure the prominence of scientific journals by taking into account not simply the number of citations that a journal receives, but also the prestige (in terms of citations received) of the journals that cite it. Journals that receive many citations from prestigious journals are considered highly prestigious themselves and, by iteratively passing prestige from one journal to another, a stable solution is reached which reflects the relative prestige of journals (Bollen et al. 2006:672). This way of measuring prestige is the basis of the algorithms for evaluating the status of web pages developed by Kleinberg (1999) and the founders of the Google search engine Brin and Page (1998). These algorithms have been recently adapted by Batagelj (2003) for the software Pajek. Hubs and Authorities stand in a mutually reinforcing relationship: Authoritative patents are those that receive many citations by good Hub patents, and good Hubs are patents citing many good Authorities.

Patent documents are a fundamental source of data since each patent contains information such as the organization that developed the invention (i.e. the name of the patent assignee), its location, the technological field and the background of the invention, which provides an overview of the technological problems to be solved. First, we studied the technical content of patents selected by network analysis algorithms. Then we analyze the geographical and organizational distribution of patents, disclosing the relative capabilities of national organizations in generating new knowledge along the miniaturization trajectory and discussing the factors that shaped them.

There are obvious limitations in using patent citations for measuring knowledge patterns. Differences exist in propensity to cite and to use self-citations across countries and firms since different strategies are used for protecting intellectual property (Mogee 1991). Moreover, it is well known that not all inventions are patentable and not all patentable inventions are patented, because secrecy is sometime the preferred strategy for protecting inventions[9]. However, patent citations remain the best standardized proxy by which we can account for the overall evolution of knowledge systems and, most importantly, they are defined by the research community itself and not by the analyst (Mina et al. 2007). With respect to the communities that are relevant for this analysis, patents are a sufficiently reliable indicator of the state of knowledge. As showed by Hall and Ziedonis (2001), the propensity to patent in the semiconductor industry is remarkable. Indeed, semiconductor firms are often engaged in “patent portfolio races” aimed at reducing concerns about being held up by external patent owners and at negotiating access to external technologies on more favorable terms.

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[9] See Pavit (1985), Griliches (1990), Jaffe and Trajtenberg (2002) for a discussion on the usage and limitations of patent documents.

Other limitations of this methodology relate the patent database we used. First, the early phase of emergence of the miniaturization trajectory, from the late 1950s to the early 1970s, is not included in our database since citations of patents issued before 1976 are not available in an electronic format. However, we believe that this did not significantly biased the results relating to the period covered by our analysis, because the patent database was built after 'testing' different key-words strategies and has been validated on the basis of the results it produced. Second, this study has used an US database, which is to some extent biased toward US organizations. This notwithstanding, the pattern of industrial leadership in the semiconductor industry seems to be well reflected by the patenting activity of the USPTO, as Fig. 2 shows.

Insert Fig.2 about here

4. Results

4.1. Incumbents, new entrants and firms' size

Fig. 3 shows a reduced version of the citation network. The size of vertices and the thickness of arcs represent the relative importance (i.e. the traversal weights) of patents and citational links, respectively[10]. This graph highlights the rich complexity of the knowledge contributions from which the miniaturization trajectory emerged and grew, together with some important citational links and patents. Although the graph does not provide any information on the pattern of knowledge advancement, it is already possible to note that the major knowledge contributions (IBM_1985, TI_1989, IBM_1976, IBM_1984, IBM_1981, TI_1994) were generated by IBM and Texas Instruments (TI), and focused on the most severe challenge stemming from the advancement of the miniaturization process, namely testing for functional performances ever more complex integrated circuits.

Insert Fig. 3 about here

Fig. 4 contains the main subnetwork, which shows the time evolution of a further reduced version of the citation network. By moving along the vertical axis, at each time period it is possible to capture the converging and diverging paths of inquiry that the community of practitioners traced by searching solutions for the main technological problems arising from the increasing integration. All paths depart from a common exploratory base (i.e. patents in the bottom layer of the figure). In this early phase, ranging between the late 1960s and the early 1970s, practitioners dealt with PCB computer systems and methods for integrating computer system components. Among these contributions, we find patent TI_1973, which disclosed the first microprocessor. This is an important point for the validation of our database because the microprocessor is the most important

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[10] For presentational purposes, only the most important vertices were labelled with their code. See Tab. 1 in the Appendix for more details on the patents characteristics. Each patent document can be completely visualized at http://patft.uspto.gov/netahtml/PTO/srchnum.htm.

invention of the semiconductor technology since the discovery of the IC and can be considered the first "computer on a chip" (Betker et al. 1997). Following the microprocessor breakthrough, we observe a distinctive pattern of closure in the network that starts from patent IBM_1976 and culminates with patent TI_1989. Patents issued in this period were mainly generated by IBM and TI, and relate to the advancement of EDA tools and the development of methods for testing LSI and VLSI circuits. Most of these contributions correspond to the major patents showed in Fig. 3 and to patents selected by both the CPM and the Main Path algorithm. Since the 1990s a wider variety of paths are explored. In particular, from patent TI_1989 the thinnest arc is leading to the right branch, which is detected by the Main Path, while the strongest arc leads to the left branch, which is the most vital one and is detected by the CPM.

Insert Fig. 4 about here

Fig. 5 illustrates the CPM path, which captures the most important stream of growth that emerged along the last 30-year development of the miniaturization trajectory[11]. The analysis of CPM patents highlights the high technological cumulativeness of the integration process that evolved through the technological eras of the miniaturization trajectory and led LSI microprocessors to become VLSI microprocessors and finally SoCs, with both hardware and software embedded. Along this process, practitioners' research efforts focused on the test, verification and debugging phases of the systems design with the aim of reducing the costs associated with the increased integration of ICs, and in the end addressed one of the most recent solutions proposed for facing the high sunk costs associated with the SoC design, namely the PSoCs.

By looking at the organizations where CPM patents were realized, we observe that, until the second half of the 2000s, the main players were established and historically integrated companies. In particular, the LSI era was dominated by IBM, at that time the most important computer company and IC manufacturer, which built most of the key components of its systems in house. Later, in an attempt to speed up PCs time to market, IBM chose to source operating systems and microprocessors from Microsoft and Intel, respectively. The VLSI era was dominated by TI, which pursued an integrated strategy until its recent decision to use foundry partners for its 32 nm process technology (LaPedus and Clarke 2007). The main SoC advancements were generated by the some of most important US microprocessors companies including Intel, Advanced Micro Devices (AMD), and Motorola. These companies focused on testing and debugging microprocessor systems, which in the 1990s became arduous challenges because of the simultaneous increase of clock speed and microprocessors ability to execute instructions in parallel. The developments concerning PSoCs were generated by Actel, a Silicon Valley fabless founded in 1985 and active in the PDLs market. All patents selected by the CPM came from US companies, with the notable exception of the Italian-French STMicroelectronics (STM), whose contribution deal with the improvement of communication among systems components, another prominent technological aspect involved

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[11] See also Tab. 2 in the Appendix for more information about the patents characteristics.

in the SoC design. STM was formed in 1987 by the merger of state-owned companies SGS Microelettronica and Thomson Semiconducteurs.

Insert Fig. 5 about here

Compared to the CPM, the Main Path (Fig. 6) shows a higher degree of technological cumulativeness. As noticed before, the Main Path stars to significantly diverge from the CPM since the second half of the 1990s. While in this period CPM patents deal with EDA tools and microprocessor advances, Main Path patents continued to focus on IC tester apparatus with the aim of developing faster and cheaper in-circuit testing (i.e. ‘single test chips’). This research led in 2000s to the development of new tools for evaluating ICs functionality (JTAGs and TAPs), while the advancements on microprocessor performances disclosed by CPM patents led to the development of PSoCs. The Main Path also displays a higher degree of organizational cumulativeness, being largely dominated by TI.

Insert Fig. 6 about here

The CPM and Main path algorithms enabled the reduction of 41,787 patents in our database to two main paths. While looking at these paths is insightful, the variety of the complementary and competing areas of search contained in the whole citation network is ignored. The Island algorithm, by identifying the main clusters of inventions in the entire research space of the miniaturization trajectory, allows us to map all major specialized bodies of knowledge that contributed to the advancement of the miniaturization process and that benefited from the diffusion of miniaturized semiconductor components. From over 3,000 clusters of patents emerged from the Island algorithm, we selected 80 on the basis of their size and relevance[12]. We found three large clusters of inventions (Main Islands). The first one regards the same search field of the CPM and the Main Path and includes all their patents as well. Therefore, this Island (CPM Island) represents the body of knowledge most closely connected with the main directions of growth of the miniaturization trajectory. The second Main Island concerns microfluidics, which deals with the behaviour, control and manipulation of the fluids in the sub-millimetre scale. Microfluidic chips are widely used in inkjet printer heads, and have become common for applications in analytical chemistry research, medical diagnostics and the like, where sample sizes may be very small and analysed substances very expensive (e.g. Lab-on-a-chip). The third Main Island relates to digital optical communications systems where semiconductor devices, in particular light-emitting diodes (LEDs) and laser diodes, are used like transmitters. Other prominent Islands regard mainly the advancement of semiconductor process technologies (chemical-mechanical planarization techniques, mask manufacturing methods etc.), the development of single electronic components, especially memory devices, and a variety of

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[12] Islands are available from the author upon request.

electronics products including consumer electronics products, automotive applications and medical devices. Fig. 6 shows an example of a technological Island, while Tab. 1 shows the geographical and organizational distribution of patents selected by technological Islands, in both the time period considered (Islands$_{1976-2008}$ and Islands$_{2000-2008}$). By looking at the total number of patents granted to firms during the whole period considered (Islands$_{1976-2008}$), we can see that US firms generated most of the contributions, followed by Japan and European countries.

Insert Fig. 7 and Tab. 1 about here

By analyzing the technological content of patents selected by Islands$_{1976-2008}$, we obtained the following results. Japanese companies focused especially on the development of consumer electronic products and automotive applications. They contributed as well to the fields of electronic components and communication technologies. The main players were established Keiretsu including Hitachi, Mitsubishi, NEC, Toshiba, Matsushita, and Canon, with the notable exception of Sony. However, the presence of Japanese firms in the CPM Island and the other Islands closely related to the main directions of growth of the miniaturization trajectory resulted rather marginal. Japanese contributions were minor even in the clusters relating memory devices. European companies were involved in almost all technological fields, but they never played a dominant role. They were especially active in the areas of automotive devices, consumer applications, and electronic components with Siemens, Philips, STM, Bosch, and Nokia. US companies generated most of the contributions in all technological Islands, with the only exception of consumer electronic products, where Japanese companies play the major part. IBM, ADM, Motorola, TI, and Intel contributed to many areas, especially to the CPM Island and semiconductor process technologies. Micron Technology was particularly active in memory devices, Xerox in MEMS applications[13], HP in the microfluidics, and AT&T in the communication field. Specialized biotech and life science companies were the main players in the clusters relating microfluidic and medical technologies. As showed in Tab. 1, SEA companies contributed marginally to the generation of patents contained in Islands$_{1976-2008}$.

In order to understand if this is a result of the relatively recent entry of these countries into the semiconductor industry, we applied the Island algorithm to a reduced database starting from 2000 (Islands$_{2000-2008}$). Indeed, the Island algorithm maps the composition of the technological knowledge that contributed to the advancement of the miniaturization trajectory from 1976 to 2008. In doing so, it privileges local connectedness among patents throughout the whole period considered and tends to neglect important research areas with a short history (Mina et al. 2007). As showed in Tab. 1, Islands$_{2000-2008}$ capture the emergence of SEA countries and highlights that US and Japan generally preserve their position, while the knowledge contributions of European

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[13] Micro-electromechanical systems (MEMS) integrate on the same silicon substrate mechanical elements, sensors, actuators, and electronics. MEMS dimensions are very small, ranging from 20 μm to 1 μm, and are currently used in a variety of consumer electronics products and medical applications.

countries sensibly lessen. SEA companies focused especially on testing for manufacturing defects, packaging technologies, and consumer electronics products. The main players were the Korean business groups Samsung and, to a lesser extent, Hyundai and LG. The few Taiwanese patents were generated by many and relatively small companies including Genesis Photonics, Taiwan Semiconductor Manufacturing, and Macronix International. However, SEA companies did not substantially contributed neither to the clusters relating memory devices nor to those concerning semiconductor process technologies, where US historically integrated firms continue to dominate.

It is interesting to note how practitioners' efforts focused on different research fields over time by comparing Islands$_{2000\text{-}2008}$ with the main clusters emerging from the whole period considered (Islands$_{1976\text{-}2008}$). In particular, three areas gain greater importance: the optical communication systems, the developments concerning the SoC design challenges, and a variety of semiconductor sensors applications. Conversely, the clusters relating to microfluidics, automotive and medical devices sensibly lessen. Other relevant results that we obtained from the analysis of Islands$_{2000\text{-}2008}$ regard the increased weight of relatively new, small and specialized companies, especially in the areas concerning the SoC design challenges. Indeed, these bodies of knowledge were importantly developed by the fablesses Xilinx, Actel, Altera, and Broadcom and by the EDA company Cadence Design Systems. The contributions of such firms mainly focused on PSoCs and PDLs, which employ technologies characterized by higher flexibility, lower sunk costs, and faster development times. Conversely, the developments concerning the SoC challenges that require more complex technologies and a closer coordination between design and manufacturing (i.e. IP test and verification, communication among IP blocks, NoCs), were disclosed by historically integrated and established firms including IMB, TI, ADM, STM, and Intel. Fablesses partially contributed to the fields of electronic components, IC testing, communication technologies, and computer network security as well. The most active firms were Cirrus Logic, Cisco Systems, and Broadcom. Fabless and other relatively new, small and specialized companies are mostly concentrated in the Silicon Valley.

4.2. Public and scientific organizations

The CPM and Main Path algorithms identified the main streams of growth of the miniaturization trajectory, while the Island algorithm mapped all major specialized bodies of knowledge that grew complementarily. The Hubs and Authorities algorithm allows us to further explore the pattern of knowledge advancement by selecting the core inventions that laid the foundation of the miniaturization trajectory (Authoritative patents) and the patents that best developed them (Hub patents). Tabs. 2 and 3 report the ten highest ranked Hub and Authoritative patents.

Insert Tabs. 2 and 3 about here

The core inventions of the miniaturization trajectory were generated in the 1980s, while Hub contributions came in the late 1990s. Both Hub and Authoritative patents deal with parallel computing systems[14] and focused on the technological problems concerning the development of parallel processors, with the aim of increasing the processing capacity and operating speed of computers. The main applications of parallel processors are supercomputers used for the solution of advanced computation problems. The term supercomputer is relative, since it refers to computers that are at the frontline of the current processing capacity. The level of performance required to make a computer a supercomputer has rapidly grown over time and today's supercomputers typically become tomorrow's ordinary computers. This is the reason why supercomputing technologies, by continuously pushing the frontier of computers processing capacity, emerged as the core inventions of the miniaturization trajectory. While Authoritative patents focused mostly on increasing the number of processors operating in parallel, Hub patents were especially devoted to the task of integrating on the same chip ever more advanced processors "capable of massively parallel processing of complex scientific and business applications" (Pat No. 5794059). This field of inquiry has recently led to the development of Multicore System-on-a-Chips (MSoC), which integrate a large number of multiple processor cores on a single chip. IBM, which in the 1990s best developed these technologies by generating all Hub patents, has lately realized the Cyclops-64 architecture, intended to create a supercomputer built on MSoC technology (Zhang et al. 2006), i.e. a "supercomputer-on-a-chip".

As showed in Tab. 2, US universities and military agencies played a decisive role in laying the foundations of the miniaturization trajectory. Four out of the ten highest ranked Authoritative patents were generated by US universities. Those were the Purdue University, which started to work at the semiconductor technology since the World War II (Henriksen 1987), and some of the most prestigious US private research universities including the Massachusetts Institute of Technology (MIT), the Johns Hopkins University, and the Duke University. Military government agencies supported the realization of Authoritative Pat No. 4380046, 4523273 and 4720780[15]. As reported in Government Interest field of these patents, the funding agencies were the NASA, the Air Force, and the Navy, respectively. A clear description of the technological objective of these contributions can be found in the background of the invention of Pat. No. 4380046, which points out the need of meeting the "increasing requirements for multidimensional data processing computers that are fast enough to operate in real time on two or more dimension data (such as two dimensional imaging data) and compact enough to be carried on board in satellites, missiles or spacecraft". Patents falling within the Government Interest class and aimed at increasing the operating speed of processors emerged in both the Main Path (Pat No. 5600788) and the CPM Island as well (Pat No. 4079455, 4597080, 4720780). These contributions were generated in the 1980s

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[14] Parallel computing is a form of computation in which many calculations are carried out simultaneously, operating on the principle that large problems can be divided into smaller ones, which are then solved concurrently, i.e. in parallel (Di Kuan-Ching 2009:857).

[15] Patents filed with the USPTO may contain a field labelled "Government Interest", which provides data that indicate any interest or right of the US government on a particular patent. This interest may arise for several reasons, but most frequently, at least in our case, it indicates that the invention received a financial support by the government.

by RCA, TI, and The Johns Hopkins University with the support of the Army, the Air Force, and the Navy, respectively. The US government interest in supercomputing technologies for military purposes, i.e. the cold war, and the considerable involvement of the US national laboratories as sponsors and customers for supercomputers has been extensively documented (Mackenzie 1991, Williams 1985, Metropolis and Nelson 1982). According to Mackenzie (1991), the sheer concentrated purchasing clout of military agencies and their pursuit of a single dominant objective (the floating-point arithmetic speed) played a major part in establishing the criterion of supercomputer status, while the R&D at the Livermore laboratory[16] also influenced how that performance criterion was measured.

The other core inventions of the miniaturization trajectory were generated by Thinking Machines, an important supercomputer manufacturer heavily involved in US military activities, and by a number of US aerospace and defence companies including Goodyear Aerospace, Hughes Aircraft and Martin Marietta. Other knowledge contributions disclosed during the 1970s and the 1980s by US companies active in the fields of defence, aerospace, and supercomputers emerged in the CPM Island as well[17]. Since in the 1970s and the 1980s US military agencies were the main large customer for aerospace, defence and supercomputer technologies, these results suggest that the military demand, both real and potential, played a critical role in shaping the decisions of the above mentioned companies to invest for developing those technologies. In this sense, the government demand acted as mechanism of knowledge accumulation in these fundamental areas of search.

Further relevant information about the role played by scientific and public organizations in the development of the miniaturization trajectory are provided by the major technological Islands. With regard to the US case, universities and government agencies generated the 12.2% of the total US patents emerging from technological Islands$_{1976\text{-}2008}$, while patents falling within the Government Interest class amount to 6.3%[18]. These results are significant, especially if we consider that the early period of the miniaturization trajectory, when the US government involvement was more prominent, is not covered by our database.

US universities and research institutes played a particularly relevant role in the generation of those clusters of inventions concerning optical communication systems, microfluidics, mass spectrometry[19], medical devices, and semiconductor sensors applications. The Stanford University and the Bell Laboratories were especially active in developing optical communication systems, with a focus on laser systems, while the

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[16] The Lawrence Livermore National Laboratory is part of the system of facilities and laboratories overseen by the US Department of Energy, the former Atomic Energy Commission.

[17] Aerospace and defence companies: Goodyear Aerospace (Pat No. 3800289, 3812467, 3936806), International Telephone and Telegraph (Pat No. 4507748, 4580215), Litton Systems (Pat No. 3988717), Raytheon (Pat No. 4691161), and Rockwell International (Pat No. 5544311). Supercomputer companies: RCA (Pat No. 3462742, 4079455), Data General (Pat No. 3737866, 4071890), Control Data (Pat No. 4527249), Cray Research (Pat No. 4636942), and Floating Point Systems (Pat No. 4891751).

[18] These include patents granted to firms (37.3%), universities (29.3%), public agencies (28%), and patents without any assignee (5.3%). If patents granted to public agencies and universities are excluded, the percentage of patents in the Government Interest class falls to 2.7% of the total US patents emerging from Islands$_{1976\text{-}2008}$.

[19] Mass spectrometry is an analytical technique for the determination of molecules elemental composition and chemical structures. Mass-spectrometers were large, heavy, and expensive. The research efforts of this Island are devoted to disclose methods for manufacturing miniaturized high performances mass-spectrometers, e.g. Mass Spectrometer on a Chip

University of Pennsylvania stand out in the microfluidics field. The primary developers of mass spectrometry technologies were The Charles Stark Draper Laboratory and the California Institute of Technology, while in the field of medical devices the main contributions from universities were generated by the MIT and the Georgia Tech Research Corporation, an organization that supports R&D at the Georgia Institute of Technology.

As to the US government, the analysis of technological $\text{Islands}_{1976\text{-}2008}$ highlights that in the 1970s and the 1980s the interest of national agencies was especially directed at the areas concerning electronic components, and, to a lesser extent, optical communications systems. The main funding agencies of those decades were the Department of Energy (DOE) and its predecessor – the Atomic Energy Commission, the Navy, the Air Force, and the Army. DOE is the most active US agency in sponsoring basic and applied scientific research through its articulated system of facilities and national laboratories – the DOE's National Laboratories and Technology Centers. Since the 1990s, the activity of the US government shifted towards the emerging research areas of the miniaturization trajectory and focused especially on microfluidics, optical communications systems, medical devices, mass spectrometry, and semiconductor sensors applications. The major funding agencies were the Advanced Technology Program (ATP) in the microfluidics field, the National Science Foundation in the area of optical communications systems, the Department of Navy and the National Institutes of Health in the field of medical devices, the NASA and the DARPA in mass spectrometry developments, and the Department of Energy in semiconductor sensor applications.

Compared to the US, the contributions of universities and government agencies in Japan and Europe were by far less considerable, amounting to 6% and 4.4% of the total Japanese and European patents emerging from the technological $\text{Islands}_{1976\text{-}2008}$. The most active Japanese organization was the METI's Agency of Industrial Science and Technology (AIST), while the sporadic contributions of European public agencies were mainly generated by the UK Ministry of Defence, the French Commissariat a l'Energie Atomique, and the UK Atomic Energy Authority.

Finally, with regard to SEA countries, the share of universities and government agencies on the total patents granted to Korea, Taiwan, and Singapore was 15.7%, 23.7%, and 16.7%, respectively[20], confirming that SEA governments played an important role in the generation of the knowledge bases that pushed the catching-up of these countries. In Korea, two main agencies emerged with important contributions in the area of communication technologies: the ETRI (Electronics and Telecommunications Research Institute) and the KAIST (Korea Advanced Institute of Science and Technology). The contributions of the Taiwanese government focused on the areas of electronic components and semiconductor process technologies and were generated by the ITRI (Industrial Technology Research Institute).

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[20] These data refer to $\text{Islands}_{2000\text{-}2008}$, since the data referring to $\text{Islands}_{1976\text{-}2008}$ are not significant for SEA countries.

5. Discussion

The pattern of leadership, as disclosed by the geographical distribution of knowledge, highlights the US dominance in the generation of the most important developments, the Japanese strength in the specialized bodies of knowledge related to consumer technologies, the overall lagging-behind of European countries, and the emergence of SEA countries. Even considering that our database is to some extent biased toward US organizations, the US leadership appears to be solid and secure. Conversely, the lagging-behind of European countries seems generalized and hardly reversible. Indeed, European firms lost out not only to US, but even to Japan and SEA countries. This suggests that the declining industrial performance of European countries is rooted in a deeper decline in their capabilities of generating new knowledge.

The organizational distribution of knowledge shed light on the relative capabilities of national organizations in generating new knowledge along the miniaturization trajectory, allowing us to discuss the main sources of leadership. The extent and relevance of the knowledge generated by US universities and government agencies show that public and scientific organizations played a critical role even during the last 30-year evolution of the semiconductor industry. They developed both the advancements in processor technologies (i.e. processors capacity and operating speed) that laid the foundation of the miniaturization trajectory and many new specialized bodies of knowledge (e.g. optical communication systems, microfluidics and medical devices). US agencies acted on both the supply side, by providing large scale funding of R&D, and the demand side, as large sophisticated users of electronic equipments. As noticed by Mowery and Nelson (1999), the structure of the university system and public R&D programs appears to be as important as the magnitude of government support in determining the performance of US public and scientific organizations.

US firms showed remarkable capabilities in generating new knowledge along the miniaturization trajectory. Relatively small, specialized and new companies played a role more important in US than elsewhere, but their dynamism appears to be a relatively recent phenomenon, by and large linked to the process of vertical specialization that occurred mostly in US, where the size of the industry and the scale of its markets are larger. The most active firms were concentrated in the Silicon Valley and exploited the new market segments opened by the process of vertical specialization providing technical solutions which are extremely creative, flexible and, at the same time, relatively less complex and expensive (e.g. PSoCs and PLDs). Such capabilities appear to be deeply rooted in the peculiar culture of the Silicon Valley and in its local networks of institutions supporting entrepreneurial start-ups (Patton and Kenney 2005). We also found that, compared to fabless and EDA companies, foundries and IP providers played a marginal role. This provides little evidence that SoCs complexity and their IP blocks structure are currently spurring a networked industry structure based on the licensing of IP blocks (Somaya and Lyinden 2003).

A relatively small collection of large and established US companies maintained leadership over the whole period considered, commanding over the most important developments that characterized the evolution of the miniaturization trajectory in the last 30 years, i.e. microprocessor systems. These technologies are highly complex and proved extremely important because of their general-purpose nature and spill-over effects on other technologies. As argued by many studies, the scale and the pattern of domestic demand, which greatly benefited from the strength of computer industry, played an important role in helping focus US firms on these technologies. However, exploiting this demand requires that firms continuously bet on the generation of new and expensive knowledge. In doing that, US firms greatly benefited from the advances made by public and scientific organizations in processors performances (i.e. capacity and operating speed). By drawing on these knowledge bases, firms could mainly focus on IC testing technologies aimed at reducing the costs stemming from increased integration of microprocessor systems. The continuous decline in price/performance ratios for microprocessor systems, in turn, led to their diffusion into a steadily expanding array of new market segments, some of them requiring new and specific knowledge bases. As emerged from technological Islands on optical communication systems, microfluidics and medical devices, US communication, biotech and life science companies showed superior capabilities of generating new knowledge in these fields as well. Once again, if the larger size of US market motivated firms to invest in these technologies, public and scientific organizations were indispensable in providing firms with the knowledge bases for exploiting the new market segments.

Our results confirm that domestic demand played an important role in focusing Japanese and European firms on consumer and automotive technologies (Langlois and Steinmuleller 1999). The strength and sophistication of Japan in generating these bodies of knowledge reflect the particular managerial and organizational characteristics of its business groups, which benefited, on the one hand, from a number of supporting institutions in the financial and labour market (Aoky 1990) and, on the other hand, from the industrial and trade policies implemented by the government during the catching-up (Dosi 1984, Lynn 2000). However, by focusing mainly on consumer applications, Japanese business groups gradually lost control over the major complex and general-purpose technologies, finally restraining their capability in generating new knowledge along the most important developments and new areas of inquire of the miniaturization trajectory. The difficulties of Japanese business groups in expanding significantly their knowledge bases beyond consumer technologies may have been favoured by the relatively small scale of knowledge generated by public and scientific organizations. Indeed, in Japan, university research proved less prolific than in US, and government policies, which put low emphasis on R&D funding, showed to be less effective in supporting the generation of frontier knowledge advancements. Relative to Japan, European firms did not benefit from comparable supporting institutions and policies during the catching-up phase. Consequently, their capability of acquiring and generating new knowledge for exploiting domestic demand was minor. These knowledge gaps cumulated over time and were exacerbated by both the inefficiency of governments' R&D programs and the relative weakness of university research.

SEA countries proved capable of quickly emerging as players, especially thanks to the strength of Korean business groups in generating specialized bodies of knowledge relating consumer applications. As highlighted by the literature (Hong 1997, Mathews 1997, Tung 2001) and showed by our results, SEA governments played an important role in supporting the acquisition and generation of new knowledge. Comparatively, domestic demand had a minor impact since, at least until the late 1980s, it was rather low and mainly related to labour-intensive technologies (i.e. assembling and packaging technologies). Relative to Taiwan, Korea benefited from the organizational and managerial capabilities of its business groups, which share many characteristics with the Japanese ones and were supported by institutions and policies in many respects similar to those of Japan. However, the few incursions of SEA firms in the areas of the most important developments and, more in general, the relatively marginal role they played in generating new knowledge suggest that SEA countries still need to strengthen their national knowledge bases and expand them beyond the bodies of knowledge acquired during the phase of emergence. This is especially true for Taiwan, due to its relatively weaker industry structure.

6. Conclusion

In this paper we have taken as a unit of analysis a whole technological trajectory, namely the miniaturization trajectory, one of the most stable and influential dynamics that have characterized the evolution of modern computing, communications, manufacturing and transport systems. We built a USPTO database of patents granted between 1976 and 2008 for the miniaturization trajectory and investigated it through four algorithms for the analysis of citation networks. The results disclosed the pattern of knowledge advancement underlying the last 30-year evolution of the miniaturization trajectory, identifying its core discoveries, main streams of growth, and major clusters of inventions.

Firstly, we studied the technical aspects involved in the pattern of knowledge advancement. The core discoveries that laid the foundation of the miniaturization trajectory deal with the development of parallel processors with the aim of increasing the operating speed and processing capacity of computers. The main streams of growth of the miniaturization trajectory focus on ICs' testing challenges with the aim of reducing the costs associated with designing ever more integrated ICs. The clusters of inventions capture the major specialized bodies of knowledge that contributed to the advancement of the miniaturization trajectory, as well as the variety of technological fields that over time benefited from the realization of miniaturized semiconductor components. They range from semiconductor process technologies to microfluidics and consumer products.

Secondly, we analyzed the geographical and organizational distribution of the pattern of knowledge advancement. The geographical distribution highlights the solidity of US leadership, the difficulties of Japan in substantially expanding its knowledge bases beyond consumer technologies and the need of SEA countries to strengthen their knowledge bases. The lagging-behind of European countries seems to be generalized and hardly reversible. This suggests that the declining industrial performance of European countries is rooted in a deeper decline in their capabilities of generating new knowledge.

The organizational distribution of knowledge shed light on the relative capabilities of national organizations in generating new knowledge along the miniaturization trajectory, allowing us to discuss the main sources of leadership. The scale and the pattern of domestic demand have been an important source of leadership, but proved to have long-lasting effects when coupled with broad and high-quality "knowledge infrastructures" generated by public and scientific organizations. Large and established US firms maintained dominance by commanding over the most important technologies of the miniaturization trajectory, i.e. microprocessor systems. The knowledge generated by US public and scientific organizations was considerable and, above all, related to the most complex and expensive technical aspects involved in the development of microprocessor systems (i.e. processor capacity and operating speed). This provided US firms with the knowledge bases for exploiting domestic demand and allow them to focus on reducing costs stemming from increased integration of microprocess systems (i.e. IC testing technologies). The advancements made on microprocessor systems, in turn, led to the growth of new market segments (e.g. optical communication systems, microfluidics and medical devices), which were successfully exploited by US specialized companies also due to the knowledge generated in this fields by public and scientific organizations.

The industrial strategy and structure have been a significant factor for explaining the relative performance of national firms, especially when supported by specific systems of institutions and policies. In particular, the peculiar network of intuitions of the Silicon Valley greatly affected the capabilities of US small firms in exploiting the new and flexible market segments opened by the process of vertical specialization (e.g. PLDs and PSoCs). Similarly, the systems of institutions that supported the managerial and organizational characteristics of Japanese and Korean business groups importantly shaped the capabilities of these firms in exploiting consumer demand better than their competitors in Europe and Taiwan, respectively.

Active sectoral-specific policies had an important impact when governments made a strong and clearly perceived commitment to catching up with technological leaders, and designed effective industrial, trade and technological policies aimed at prioritizing the acquisition of external knowledge according to the specificities of national/regional innovation systems. This emerged both by comparing the Japanese and European cases, and the more recent experience of SEA countries. However, for countries that are already at the technological frontier, the important government policies involved wide investments in knowledge infrastructures, through the support of excellence in university research and training on the one hand, and the provision of broadly targeted R&D and procurement programs on the other hand. Conversely, when government put relatively low emphasis on the creation of solid knowledge infrastructures, like in Japan, firms gradually lost access to the most complex and expensive technologies, finally restraining their innovative capabilities. European governments failed in building a reliable commitment to catching up technological frontier and in designing effective policies aimed at acquiring external knowledge. These knowledge gaps cumulated during this period were later exacerbated by both the inefficiency of governments' R&D programs and the relative weakness of university research, resulting in the observed overall lagging-behind of European firms.

This study has of course several limitations, which provide opportunities for further research. First, this is a single technology case study and its results should be generalized with care. However, the methodology developed yields an interesting potential for applications in other high-technology industries. Second, a number of factors have been left in the background, for example the role played by the broader instituional and regulatory framework and the institutional changes that accompanied the evolution of the miniaturization trajectory. Finally, this study investigated the sources of leadership in a relatively established technological paradigm. Analyzing the pattern of knowledge advancement underlying the emergence of radically new technologies would allow discussing the sources of leadership during the phases of paradigmatic changes.

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Tables and Figures

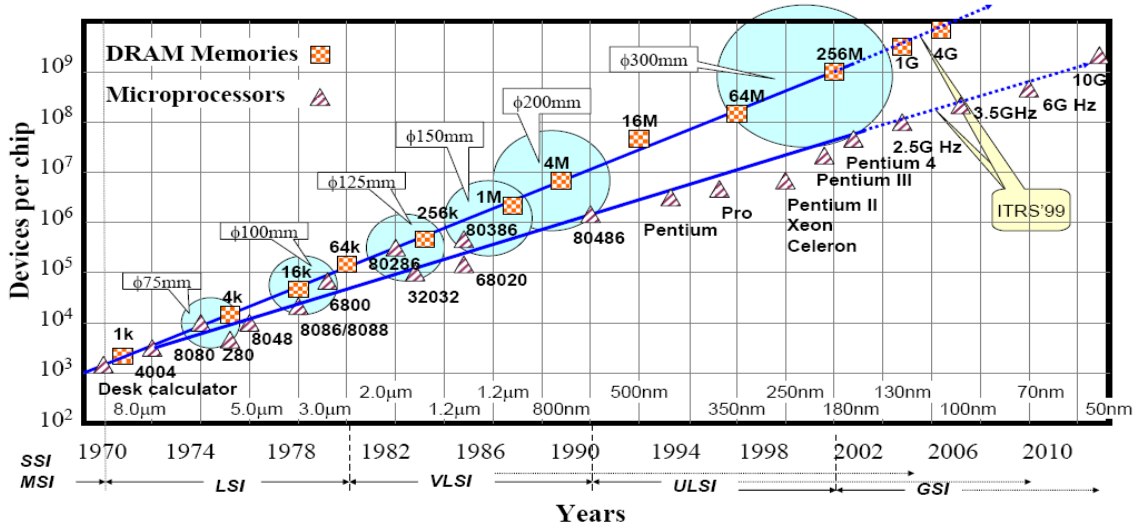


Fig. 1. Moore's Law and miniaturization trajectory
Source: Zheng (2008)

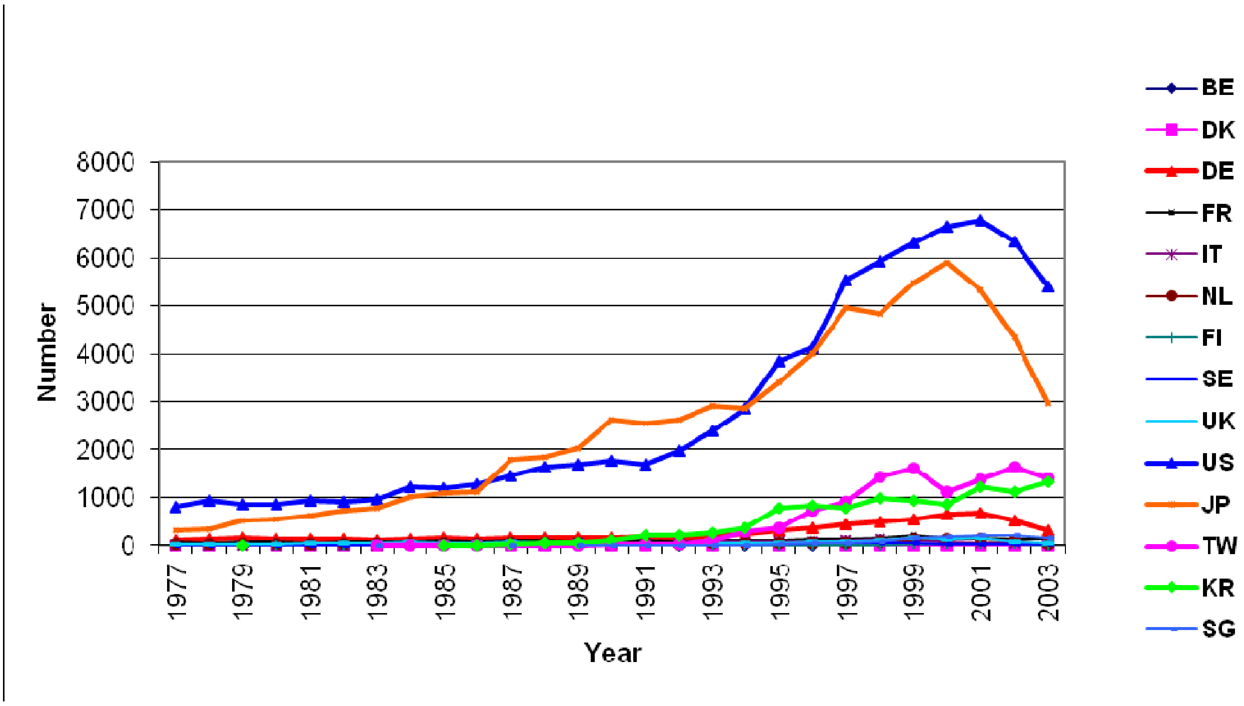


Fig. 2. Semiconductor patents granted by the USPTO by priority year at the national level
Source: Eurostat

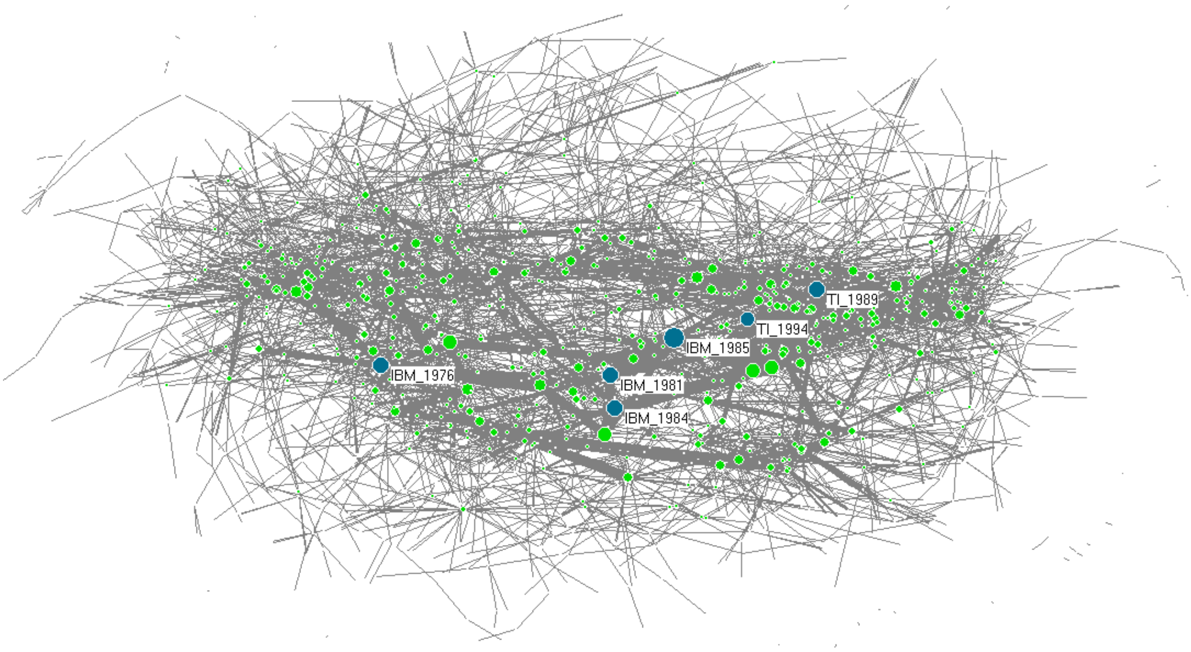


Fig. 3. Reduced version of the citation network

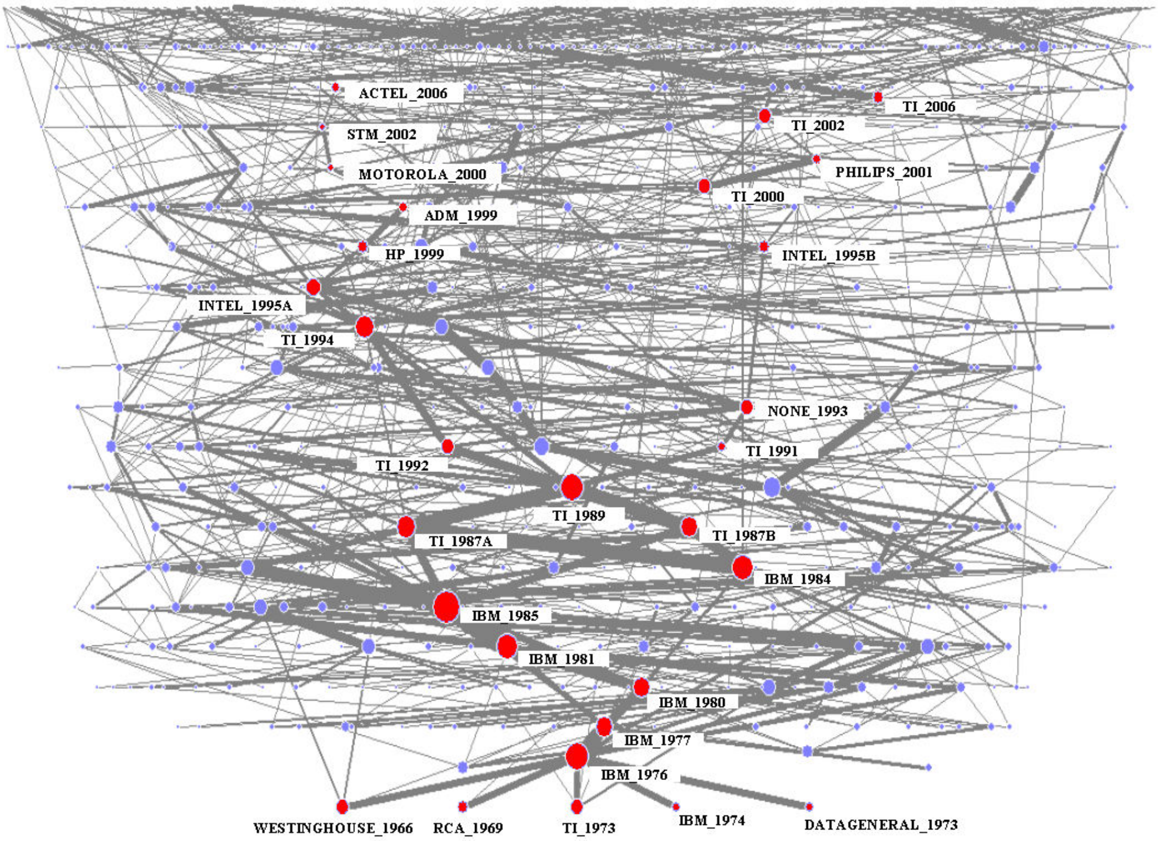
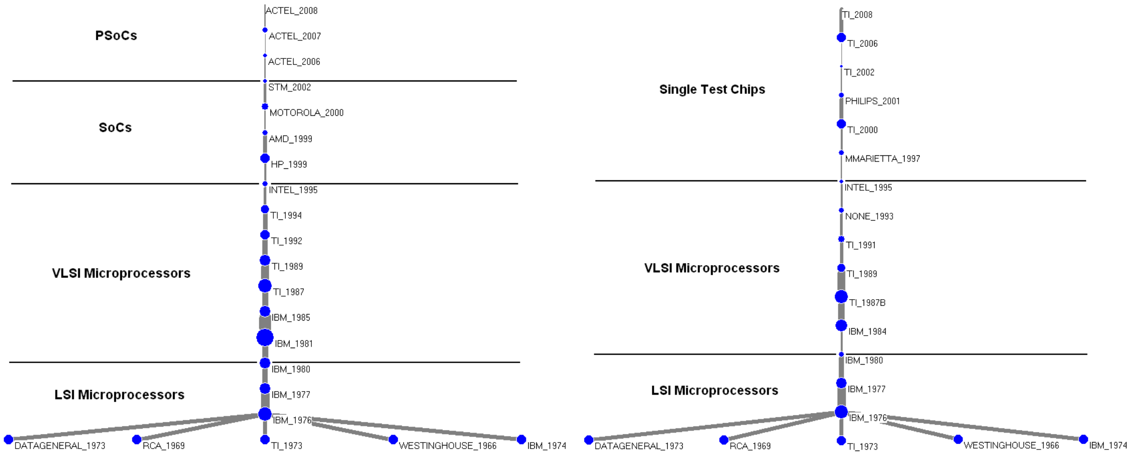


Fig. 4. Main Subnetwork



Figs. 5 and 6. CPM and Main Path

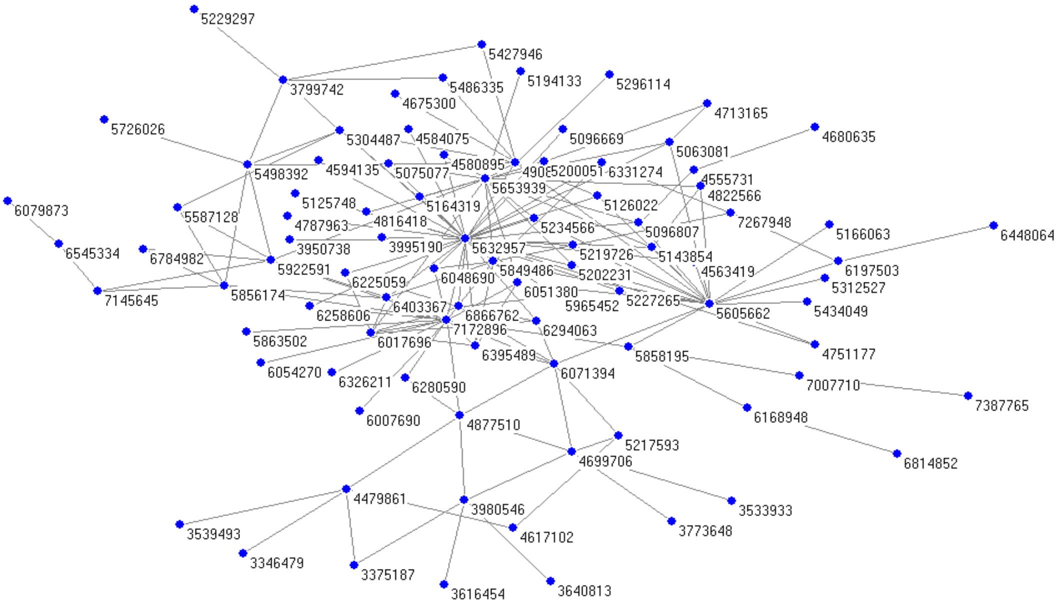


Fig. 7. Main Island ‘Microfluidics’

Tab. 1. Technological Islands, geographical and organizational distribution (%)[21]

	USA	JP	EU	SEA	Other	No Assignee	TOT
Firms	69.5	16.7	11.7	0.9	1.2	-	100
	72.3	16.1	5.7	4.6	1.2	-	100
Public Agencies and Universities	77.4	8.6	4.3	2.7	7.0	-	100
	66.4	0.8	6.4	15.2	11.2	-	100
TOT	66.1	14.9	10.2	1.1	1.7	6.1	100
	69	14.5	5.5	5.1	1.8	4.1	100

☐ Islands$_{1976-2008}$

▨ Islands$_{2000-2008}$

Tab. 2. Authoritative patents

Patent Number	Issue Date	Title	Assignee Name
4598400	July 1, 1986	Method and apparatus for routing message packets	Thinking Machines Corporation (Cambridge, MA)
4380046	April 12, 1983	Massively parallel processor computer	None
4621339	November 4, 1986	SIMD machine using cube connected cycles network architecture for vector processing	Duke University (Durham, NC)
4523273	June 11, 1985	Extra stage cube	Purdue Research Foundation (Lafayette, IN)
4720780	January 19, 1988	Memory-linked wavefront array processor	The Johns Hopkins University (Baltimore, MD)
4873626	October 10, 1989	Parallel processing system with processor array having memory system included in system memory	Massachusetts Institute of Technology (Cambridge, MA)
4739474	April 19, 1988	Geometric-arithmetic parallel processor	Martin Marietta Corporation (Bethesda, MD)
4805091	February 14, 1989	Method and apparatus for interconnecting processors in a hyper-dimensional array	Thinking Machines Corporation (Cambridge, MA)
4314349	February 2, 1982	Processing element for parallel array processors	Goodyear Aerospace Corporation (Akron, OH)
3970993	July 20, 1976	Cooperative-word linear array parallel processor	Hughes Aircraft Company (Culver City, CA)

▨ US Government Interest

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[21] The procedure to build this table is based on the name of the patent assignee listed on the patent, and did not take into account ownership relations between organizations (e.g. mother- and daughter-firms), or mergers, acquisitions and split-ups. However, patents have been assigned to countries by the author according to the companies' headquarter rather than the location listed on the patent. For example, Pat No. 6243842, which was granted to "*STMicroelectronics, Inc. (Carrollton, TX)*", has been assigned to European countries and not to US, since STMicroelectronics is an Italian-French company headquartered in Switzerland.

Tab.3. Hubs patents

Patent Number	Issue Date	Title	Assignee Name
5794059	August 11, 1998	N-dimensional modified hypercube	International Business Machines Corporation (Armonk, NY)
5963745	October 5, 1999	APAP I/O programmable router	International Business Machines Corporation (Armonk, NY)
5842031	November 24, 1998	Advanced parallel array processor (APAP)	International Business Machines Corporation (Armonk, NY)
5828894	October 27, 1998	Array processor having grouping of SIMD pickets	International Business Machines Corporation (Armonk, NY)
5822608	October 13, 1998	Associative parallel processing system	International Business Machines Corporation (Armonk, NY)
5717943	February 10, 1998	Advanced parallel array processor (APAP)	International Business Machines Corporation (Armonk, NY
5963746	October 5, 1999	Fully distributed processing memory element	International Business Machines Corporation (Armonk, NY)
5966528	October 12, 1999	SIMD/MIMD array processor with vector processing	International Business Machines Corporation (Armonk, NY)
6094715	July 25, 2000	SIMD/MIMD processing synchronization	International Business Machines Corporation (Armonk, NY
5734921	March 31, 1998	Advanced parallel array processor computer package	International Business Machines Corporation (Armonk, NY)

Appendix

Tab.1. Reduced Network

Patent Code	Patent Number	*Issue Date*	Title	Assignee Name
IBM_1985	4503537	March 5, 1985	Parallel path self-testing system	International Business Machines Corporation (Armonk, NY)
TI_1989	4872169	October 3, 1989	Hierarchical scan selection	Texas Instruments Incorporated (Dallas, TX)
IBM_1976	3983538	September 28, 1976	Universal LSI array logic modules with integral storage array and variable autonomous sequencing	International Business Machines Corporation (Armonk, NY)
IBM_1984	4441075	April 3, 1984	Circuit arrangement which permits the testing of each individual chip and interchip connection in a high density packaging structure having a plurality of interconnected chips, without any physical disconnection	International Business Machines Corporation (Armonk, NY)
IBM_1981	4298980	November 3, 1981	LSI Circuitry conforming to level sensitive scan design (LSSD) rules and method of testing same	International Business Machines Corporation (Armonk, NY)
TI_1994	5329471	July 12, 1994	Emulation devices, systems and methods utilizing state machines	Texas Instruments Incorporated (Dallas, TX)

Tab.2. CPM patents

Patent Code	Patent Number	Issue Date	Title	Assignee Name
WESTINGHOUSE_1966	3287703	November 11, 1966	Computer	Westinghouse Electric Corp.
RCA_1969	3462742	August 19, 1969	Computer system adapted to be constructed of large integrated circuit arrays	Rca Corporation
DATAGENERAL_1973	3737866	June 5, 1973	Data storage and retrieval system	Data General Corporation (Southboro, MA)
TI_1973	3757306	September 4, 1973	Computing system CPU	Texas Instruments Incorporated (Dallas, TX)
IBM_1974	3798606	March 19, 1974	Bit partitioned monolithic circuit computer system	International Business Machines Corporation (Armonk, NY)
IBM_1976	3983538	September 28, 1976	Universal LSI array logic modules with integral storage array and variable autonomous sequencing	International Business Machines Corporation (Armonk, NY)
IBM_1977	4051353	September 27, 1977	Accordion shift register and its application in the implementation of level sensitive logic system	International Business Machines Corporation (Armonk, NY)
IBM_1980	4225957	September 30, 1980	Testing macros embedded in LSI chips	International Business Machines Corporation (Armonk, NY)
IBM_1981	4298980	November 3, 1981	LSI Circuitry conforming to level sensitive scan design (LSSD) rules and method of testing same	International Business Machines Corporation (Armonk, NY)
IBM_1985	4503537	March 5, 1985	Parallel path self-testing system	International Business Machines Corporation (Armonk, NY)
TI_1987	4710931	December 1, 1987	Partitioned scan-testing system	Texas Instruments Incorporated (Dallas, TX)
TI_1989	4872169	October 3, 1989	Hierarchical scan selection	Texas Instruments Incorporated (Dallas, TX))
TI_1992	5103450	April 7, 1992	Event qualified testing protocols for integrated circuits	Texas Instruments Incorporated (Dallas, TX)
TI_1994	5329471	July 12, 1994	Emulation devices, systems and methods utilizing state machines	Texas Instruments Incorporated (Dallas, TX))
INTEL_1995	5479652	December 26, 1995	Microprocessor with an external command mode for diagnosis and debugging	Intel Corporation (Santa Clara, CA)
HP_1999	5867644	February 2, 1999	System and method for on-chip debug support and performance monitoring in a microprocessor	Hewlett Packard Company (Palo Alto, CA)
AMD_1999	5978902	November 2, 1999	Debug interface including operating system access of a serial/parallel debug port	Advanced Micro Devices, Inc. (Sunnyvale, CA)
MOTOROLA_2000	6145122	November 7, 2000	Development interface for a data processor	Motorola, Inc. (Schaumburg, IL)
STM_2002	6415344	July 2, 2002	System and method for on-chip communication	STMicroelectronics Limited (Almondsbury, GB)
ACTEL_2006	7034569	April 25, 2006	Programmable system on a chip for power-supply voltage and current monitoring and control	Actel Corporation (Mountain View, CA)
ACTEL_2007	7256610	August 14, 2007	Programmable system on a chip for temperature monitoring and control	Actel Corporation (Mountain View, CA)
ACTEL_2008	7446560	November 4, 2008	Programmable system on a chip for temperature monitoring and control	Actel Corporation (Mountain View, CA)