Groupe de Recherche en
Économie Théorique et Appliquée

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

Marianna EPICOCO

GREThA, CNRS, UMR 5113
Université de Bordeaux

&

DSLW, University of Milan

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GRETHA UMR CNRS 5113
Université Montesquieu Bordeaux IV
Avenue Léon Duguit - 33608 PESSAC - FRANCE
Tel : +33 (0)5.56.84.25.75 - Fax : +33 (0)5.56.84.86.47 - www.gretha.fr

Dynamique de la connaissance et sources de leadership: une cartographie de la trajectoire de miniaturisation dans les semi-conducteurs

Résumé

Cet article examine les capacités technologiques que les organisations nationales ont générées et accumulées le long de la trajectoire de miniaturisation, qui est la plus cruciale direction de changement affectant l'industrie des semi-conducteurs depuis son début. Notre méthode de recherche repose sur la construction d'une base de données unique des brevets et sur l'utilisation de trois algorithmes d'analyse des réseaux de citations. Premièrement, cela nous permet de cartographier la dynamique de la connaissance technologique qui sous-tend les avancées le long de la trajectoire de miniaturisation. Ainsi, nous identifions trois dimensions différentes de la dynamique de la connaissance que nous caractérisons en termes de propriétés distinctives de la connaissance. Deuxièmement, nous analysons la répartition géographique et organisationnelle de la dynamique de la connaissance. Les résultats montrent des différences significatives dans les capacités technologiques des organisations nationales, notamment à travers l'ampleur et les propriétés de la connaissance technologique que ces organisations ont générée au cours du temps. Nous montrons également que si les organisations des États-Unis sont restées fortes pendant toute la période considérée, les capacités technologiques des organisations européennes se sont considérablement érodées au cours des dernières années avec l'émergence des pays de l'Asie du sud-est.

Mots-clés : Dynamique de la connaissance; Capacités technologiques; Trajectoire de miniaturisation; Industrie des semi-conducteurs; Analyse des brevets; Analyse des réseaux de citations.

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

Abstract

This article examines the technological capabilities that national organizations generated and accumulated along the long-term evolution of the miniaturization trajectory, the most important direction of change in the semiconductor industry. By building an original dataset of patents and using three algorithms for the analysis of citation networks, we first map the pattern of technological knowledge underlying the advancement of the miniaturization trajectory. We identify three different dimensions of the knowledge pattern and characterize them in terms of distinctive knowledge properties. Second, we analyze the geographical and organizational distribution of the knowledge pattern. The results provide evidence for significant differences in the technological capabilities of national organizations, as revealed by the magnitude and the properties of the technological knowledge that these organizations generated over time. We find, among the other things, that while US organizations remained strong over the whole time period considered, the technological capabilities of European organizations were considerably eroded in the most recent years by the emergence of SEA countries.

Keywords: Knowledge dynamics; Technological capabilities; Semiconductor miniaturization trajectory; Patent analysis; Citation network analysis.

JEL: O30, O57, L63

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1. Introduction

Over the last six decades, the worldwide evolution of industrial leadership has been powerfully influenced by the growth of the semiconductor industry, due to the pervasive and general purpose nature of its technologies. During the first three decades of the industry, from the 1950s to the 1970s, US firms were uncontested leaders introducing the three basic innovations of the industry – the transistor, the integrated circuit and the microprocessor – and dominating the international market of semiconductors (Tilton, 1971; Braun and MacDonald, 1982; Dosi, 1984). In the 1980s Japanese firms began to challenge this dominance (Florida and Kenney, 1990; Callon, 1995), raising concerns among US policymakers and scholars. In the 1990s, the US resurgence (Macher et al., 1998; Langlois and Steinmueller, 2000) and the rise of SEA countries (Chen and Swell, 1996; Mathews, 1997; Kim, 1998; Cho et al., 1998) quickly changed the scenario of the previous decade. European firms remained competitive in the semiconductor market until the early 1960s (Malerba, 1985), but since then have played a relatively peripheral role in the industry (Langolis and Steinmueller, 1999). The factors behind this pattern of industrial leadership have been extensively analyzed by the mentioned literature. The main explanations have focused on the scale and pattern of domestic demand, the industrial strategy and structure, governments' policies, and on a number of national institutions, including the financial system, the labor market, and the university system.

Despite this research has greatly contributed to our understanding of the sources of leadership in the semiconductor industry, still no systematic evidence has been provided for answering the following questions. Are there differences in the technological capabilities that national organizations generated and accumulated along the evolution of the industry? Are there differences in the characteristics of the main national sources of knowledge generation, namely research organizations, government agencies and different types of firms (e.g., established versus new firms, integrated versus specialized companies)? The answers to these questions are relevant for both researchers and policymakers since in high-technology industries, industrial leadership largely depends on technological leadership, which, in turn, importantly rests on the technological capabilities that national organizations generate and accumulate over time.

The novelty of the present article is to fill this gap in the literature by mapping the pattern of technological knowledge underlying the long-term evolution of the miniaturization trajectory and the national organizations that generated it. The studies on technological paradigms and trajectories (Dosi, 1982; 1984) showed that semiconductors emerged as a result of the generation of radically new knowledge around the need for increasing miniaturization of electronic components. After the invention of the microprocessor, the realization of the "promise" contained in the new paradigm proceeded through 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 evolution of the industry, advancing for more than 50 years according to a strikingly stable rate, i.e., the Moore's law.

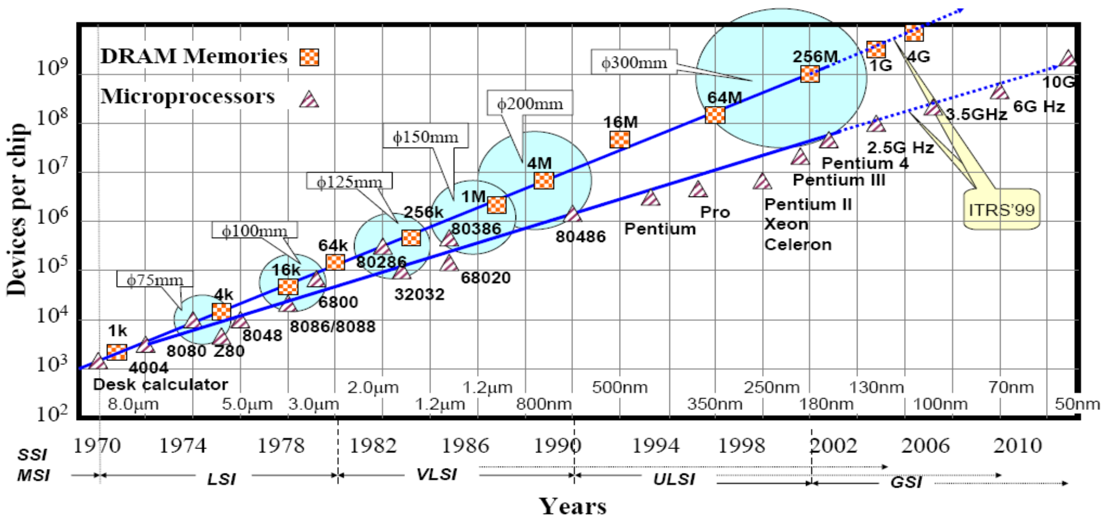
In this study, we take as a unit of analysis the miniaturization trajectory, build an original dataset of patents granted between 1976 and 2008 for the miniaturization trajectory and investigate it through three algorithms for the analysis of citation networks originating from the field of the graph theory (Batagelj, 2003). The usefulness and validity of citation network methods for mapping the technological trajectories that have characterized the evolution of specific fields has been showed by recent studies (Mina et al., 2007; Verspagen, 2007; Fontana et al., 2009; Martinelli and Bekkers, 2010; Barbera et al., 2011). Here, we use and expand such methods in order to identify different dimensions of the knowledge pattern – the core discoveries, the backbone and the major clusters of inventions of the miniaturization trajectory – and characterize them in terms of distinctive knowledge properties, namely basicness, cumulativeness and specialization. Finally, we analyze the geographical and organizational distribution of the knowledge pattern, disclosing the main national organizations at play and their technological capabilities, as revealed by both the magnitude and the properties of the technological knowledge that these organizations generated over time.

The rest of the paper is organized as follow. Section 2 is an historical overview of the miniaturization trajectory, with a focus on the most recent developments. Section 3 presents the data and the methodology. Section 4 illustrates and analyzes the pattern of technological knowledge underlying the evolution of the miniaturization trajectory. Section 5 discusses the differences in the characteristics of the main national organizations at play and in their technological capabilities. Section 6 concludes.

2. The semiconductor miniaturization trajectory

The miniaturization trajectory refers to the continuous scaling down of the minimum sizes of electronic components in order to integrate additional functionalities on the same integrated circuit (IC). This trajectory has powerfully influenced all the main directions of change of the semiconductor technology: as sizes shrink, costs per chip decrease, processing speed increases, power consumption is reduced, and final electronic products become more compact and multifunction. Figure 1 shows the evolution of the miniaturization trajectory over the last 40 years. We can see from this figure that as the advancement of semiconductor process technologies allowed scaling down[1], the number of transistors (i.e., devices) that could be integrated on the same chip increased according to the Moore's Law, which states that the number of devices 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 characterized the development of the miniaturization trajectory.

Figure 1. Moore's Law and miniaturization trajectory



Source: Zheng (2008)

A decade after the invention of the transistor, the integrated circuit (IC or chip) integrated a whole electronic circuit on a single silicon substrate, leading to an enormous performance increase and cost reduction compared with the manual assembly of circuits using discrete components.

[1] This is the process technology whereby semiconductor chips are manufactured. Transistor dimensions are measured in microns (μm). 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 nanometer (nm) unit. A nanometer is one billionth of a meter.

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 can be considered the first "computer on a chip" (Betker et al., 1997) and was a fundamental breakthrough in the semiconductor history, since it allowed the integration of a whole processor (CPU) on a single IC containing the equivalent of thousands discrete transistors. A processor is the fundamental component of computers of any era because its ability of executing a program gives computers the essential feature of programmability. The invention of the microprocessor resulted in huge increase in processing speed of computers and considerable reduction in computer costs. 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 impressive increase of ICs complexity that enabled VLSI chips demanded the invention of new design technologies in order to handle such complexity. This led to the development in the 1980s of computerized design tools, which evolved in the modern EDA (Electronic Design Automation) tools and allowed engineers to test ICs functional performances before their manufacture. Since prior to the 1980s chips were largely designed by hand, EDA tools had an important impact on productivity of IC designers. In the mid-1990s, the advancement of the semiconductor process technology pushed the miniaturization trajectory to 350-250 nm, allowing the realization of the System on a chip (SoC), which integrates a whole electronic system (e.g., a computer) on a single chip, with both hardware and software embedded (Martin, 2003)[2]. The emergence of SoCs accelerated the diffusion of semiconductor devices into a steadily expanding array of new products, ranging from consumer electronics products and automotive applications to communication technologies and medical devices.

The management of the growing complexity of SoCs put out new challenges for design methodologies, which became the source of ever higher sunk costs and created the so-called "design productivity gap": while ICs complexity and density increased rapidly following the Moore's Law, improvements in the productivity of IC designers failed to keep up (Linden and Somaya, 2003). Although in the last years many efforts have been devoted to the development of new methodologies for the SoC design, still a considerable lack of pragmatic knowledge remains among practitioners (Martin and Chang, 2003). 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). Other recent research directions addressing the SoC design challenges are the Network-on-a-Chip (NoC) and the Programmable SoC

[2] 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.

(PSoC). The NoC approach is based on the application to the SoC design of the models coming from the network design field and focuses on the development of advanced interconnect technologies for interconnecting SoC components (Benini and De Micheli, 2002). 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). PLDs are electronic components characterized by a high degree of flexibility since they can be configured by the customer or designer after manufacturing. These features, and the consequently low sunk costs of production, make PLDs suitable for many applications. PSoCs are SoCs that incorporate one or more programmable logic cores.

This historical overview provides a basis for understanding why the miniaturization trajectory dominated the whole evolution of semiconductor industry and the nature of the technical problems involved in its evolution. In the next sections we map the pattern of knowledge advancement underlying this evolution in order to disclose the technological capabilities that national organizations generated over time.

3. Data and methods

Since the work of Garfield et al. (1964), citations among scientific publications 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 new 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 for analyzing different characteristics of 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 might present limitations when the focus is on the cumulative growth of technological knowledge in a specific field[3]. More recently, a number of studies have extended the Hummon and Doreian’s techniques to the analysis of patent citations in order to map the technological trajectories that have characterized the evolution of specific fields (Mina et al., 2007; Verspagen, 2007; Fontana et al., 2009; Martinelli and Bekkers, 2010; Barbera et al., 2011).

In this article, we use the network citation methods proposed by these studies and expand them along three directions. First, we take as a unit of analysis a technological trajectory rather than a relatively narrow technological field, thus mapping the technological knowledge underlying the evolution of the main direction of change in an industry. Second, rather than focusing on one main algorithm of network analysis, we use three different algorithms. This allows us to identify different dimensions of the knowledge pattern and characterize them in terms of distinctive knowledge properties. Third, we analyze the geographical and organizational distribution of the knowledge pattern. By doing so, we go beyond the analysis of knowledge evolution and try to connect it with the sources of knowledge generation in a sector.

In our context, patents granted for the miniaturization trajectory correspond to the vertices of a network and are connected with each other by a number of arcs, which symbolize citational links

[3] See Fontana et al. (2009) for a detailed discussion of this issue.

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 cited patent represents a previously existing piece of knowledge that has been incorporated and further developed by the citing patent. Citations among patents, making explicit the epistemic links among the pieces of knowledge from which the miniaturization trajectory emerged and grew, can be used to trace its pattern of knowledge advancement.

As first step, we built a patent dataset for the miniaturization trajectory, which was extracted from the USPTO (United States Patent and Trademark Office)[4] 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 secondary sources and interviewing three experts[5]. The USPTO patents prior to 1976 do not have full-text access and it is not possible to extract them by means of a key-words search. To overcome, at least in part, this limitation and capture patents related to the earlier phase of the miniaturization trajectory, we included into the dataset also all patents cited by patents selected through the key-words search. The final dataset (i.e., patents extracted by the key-words search and their citations) contains 41,787 vertices and 121,393 arcs. We then constructed a network of citations among patents in the dataset and applied to it the following algorithms implemented by the program Pajek[6].

The first algorithm is the Critical Path Method (CPM) and captures the dominant direction of knowledge accumulation that emerged over the whole time period covered by this analysis, i.e., the backbone of the miniaturization trajectory. By computing the total number of paths linking oldest vertices in a citation network to the most recent ones, this algorithm maps all possible streams of cumulative growth of knowledge, and selects the most important one. Therefore, the knowledge identified by the CPM algorithm is expected to show a relatively high degree of technological cumulativeness. The CPM algorithm is based on the Search Path Count (SPC) method (Batagelj, 2003), which calculates traversal weights on arcs following the Hummon and Doreian's main path analysis. Traversal weights measure the importance of paths linking entry vertices in a network (i.e., patents that are not cited within the dataset) to exit vertices (i.e., patents that are not citing within the dataset)[7]. The CPM algorithm determines the path from entry vertices to exit vertices with the largest total sum of weights on its arcs.

The second algorithm is called Island and identifies the main clusters of inventions in the entire research space of the miniaturization trajectory, thus mapping the major bodies of knowledge that contributed to and benefited from the advancement of the miniaturization process. The Island algorithm 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 in the whole dataset non-overlapping subsets of vertices that, according to the arc weights, are more closely connected with each other

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

[5] Many efforts have been devoted to select and validate the key-words strategy. Professors Donatella Sciuto and Andrea Lacaita (Politecnico of Milan), and Fabrizio Rovati (STMicroelectronics) were interviewed on both the key-words strategy and the most important technological developments of the miniaturization trajectory.

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

[7] Traversal weights on arcs are calculated in the following way. In an acyclic network there is at least one entry and at least one exit. Let us denote with *I* and *O* the set of all entries and all exits, respectively. The SPC method assigns to each arc as its weight the number of the different *I-O* paths passing through the arc. This number is then divided by the total number of paths between entry and exit vertices in the network. This proportion is the traversal weight of an arc. Traversal weights on arcs and vertices are calculated simultaneously, therefore traversal weights on arcs always correspond to traversal weights on vertices. For more details see de Nooy et al. (2005).

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 characterized by a relatively high degree of specialization.

Finally, the Hubs and Authorities algorithm selects the core discoveries that laid the foundation of the miniaturization trajectory (Authorities), and their best developments (Hubs). Hubs and Authorities are formal notions of structural prominence of vertices (Brandes and Willhalm, 2002). 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 and determines its most prominent vertices. Consequently, the knowledge identified by this algorithm is expected to display a relatively high degree of basicness. The concept at the basis of the Hubs and Authorities 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 (Calero-Medina and Noyons, 2008). 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). This way of measuring prestige is the basis of the algorithms for evaluating the status of web pages developed by Kleinberg (1999) and Brin and Page (1998). Such algorithms have been later adapted by Batagelj (2003) for the software Pajek. Hubs and authorities stand in a mutually reinforcing relationship: a good authority is a patent that is cited by many good hubs, and a good hub is a patent citing many good authorities (Calero-Medina and Noyons, 2008).

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 (i.e., the address of the patent assignee), the technological field, and the background of the invention, which provides an overview of the technological problems to be solved. We first studied the technical content of patents selected by network analysis algorithms and used this information to trace the pattern of knowledge advancement that pushed the miniaturization trajectory. Second, we used the information relating to the patent assignees and their address to examine the geographical and organizational distribution of the knowledge pattern. On this basis, we disclose the main national organizations at play and their technological capabilities, as revealed by the magnitude and the properties of technological knowledge these organizations generated along the different dimensions of the knowledge pattern.

4. Results

4.1. Firms

Figure 2 shows a reduced version of the citation network[8]. The size of vertices and the thickness of arcs represent the relative importance (i.e., the traversal weights) of patents and citational links, respectively[9]. This graph highlights the rich complexity of knowledge contributions from which the miniaturization trajectory emerged and grew, together with some important patents

[8] The network has been reduced in order to allow its visualization with Pajek. The reduced network has been built following Batagelj (2003). In particular, we calculated traversal weights on arcs through the SPC method (see section 3), deleted all arcs with weights lower than a selected threshold and eliminated all resulting isolated vertices.

[9] For presentational purposes, only the most important vertices were labeled with their code. See Table 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

and citational links. Although the graph does not provide any information on the pattern of knowledge advancement, it is already possible to note that the key 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 testing phase of electronic systems design.

Figure 2. Citation network

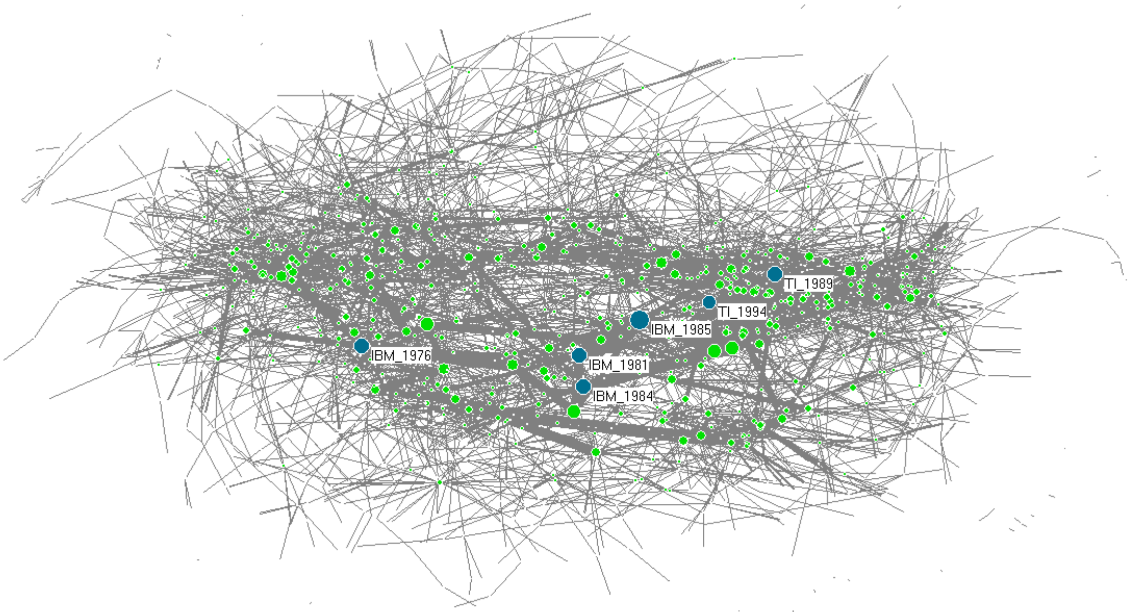


Figure 3 contains the CPM path, which captures the dominant direction of knowledge accumulation that emerged along the whole evolution of the miniaturization trajectory[10]. Starting from the bottom of the figure and moving along the vertical axis, this graph shows the sequence of knowledge contributions that formed the backbone of the miniaturization trajectory and allows us to detail the technical problems that occupied the community of practitioners over time. The analysis of the content of CPM patents highlights the high technological cumulativeness of the integration process that evolved through the technological eras of the miniaturization trajectory and led PCB computer systems to become multi-chip computer systems and finally single-chip computer systems, with both hardware and software embedded[11]. Along this process, research efforts focused on testing phase of electronic systems design (as already suggested by the previous graph), with the aim of reducing the costs stemming from the increasing integration of ICs.

By examining more in details CPM patents, we found that in the first phase, ranging from the mid-1960s to the early 1970s (i.e., patents in the bottom layer of the figure: DATAGENERAL_1973, RCA_1969, TI_1973, IBM_1974, and WESTINGHOUSE_1966) practitioners explored different solutions for integrating PCB computer systems components. Among these contributions, we found patent TI_1973, which disclosed the first microprocessor. This is an important point for the validation of our dataset since the microprocessor is the most significant innovation of the semiconductor technology during the time period covered by this analysis and the last radical innovation of the industry. Following the microprocessor breakthrough, the decades between the mid-1970s and the mid-1990s (patents from IBM_1976 to TI_1994) focused on the advancement of EDA tools and the development of methods for testing LSI and VLSI circuits. Distinctly, among these contributions, two

[10] See Table 2 in the Appendix for more information on patent characteristics.

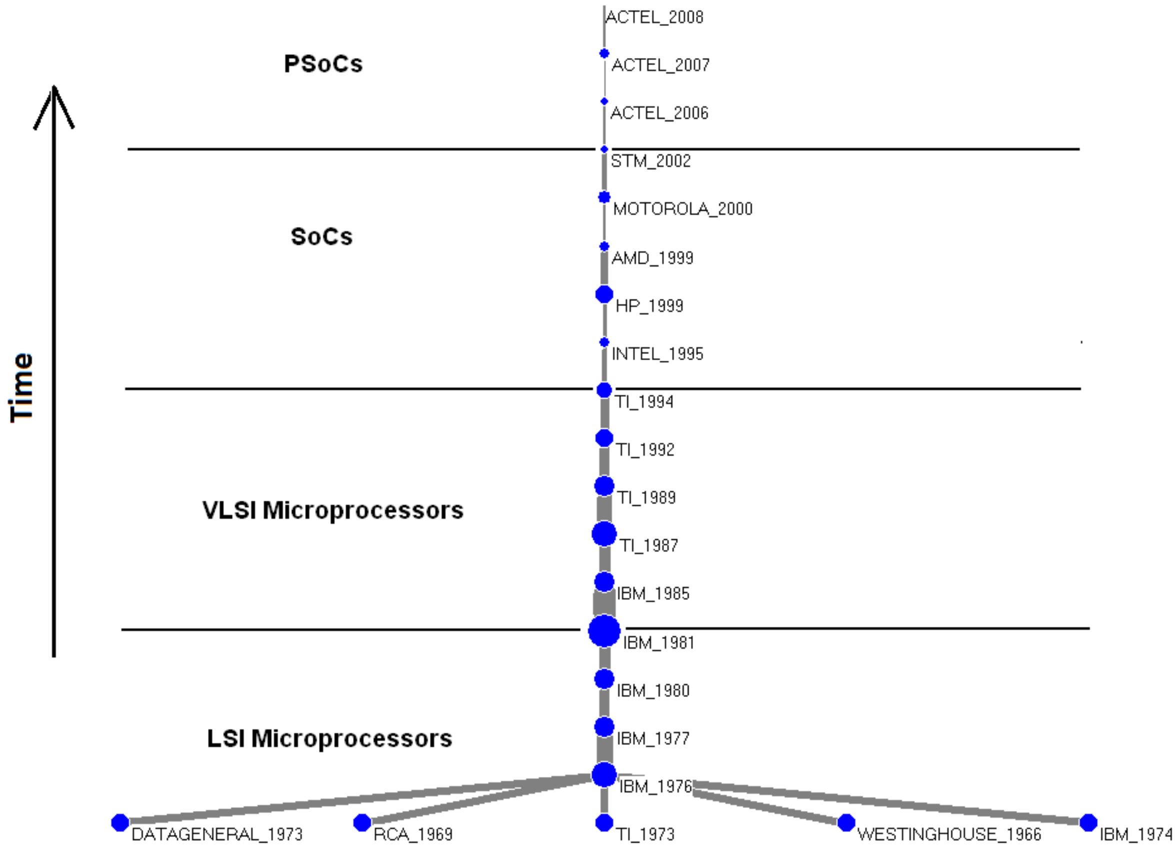
[11] PCB computer systems are computers where discrete electronic components are connected with each other and together with passive electronic components on a printed circuit board (PCB) to create an electronic circuit with a dedicated function. Conversely, in single-chip computer systems, discrete components are manufactured and interconnected, i.e. integrated, on a single silicon substrate

are particularly important, namely patents IBM_1981 and TI_1987. The former disclosed an LSI integrated circuit system fully conformed to new, for that period, design rules (i.e., Level Sensitive Scan Design), while the latter dealt with the utilization of the same techniques for testing VLSI ICs. Of interest is also patent TI_1994, which provided new methods for testing and integrating both hardware and software, and started to tackle the issue of the "design-for-reusability", thus paving the way for the subsequent SoC development.

The second half of the 1990s is the period when the most important SoC developments occur. Patents issued during those years (from INTEL_1995 to MOTOROLA_2000) focused on making more efficient hardware testing and software program debugging, in order to cope with the simultaneous increase of computers operating speed and microprocessors ability to execute instructions in parallel. This phase culminates with patent STM_2002, which dealt with the improvement of communication among systems components, another prominent technological aspect involved in the SoC design. The analysis of the last three patents that formed the backbone of the miniaturization trajectory (ACTEL_2006, ACTEL_2007, ACTEL_2008) shows that since the second half of the 2000s, practitioners are focusing on the development of one of the most recent solutions proposed for facing the high sunk costs associated with the SoC design, namely the PSoCs (see section 2).

By looking at the organizations where CPM patents were realized, we observe a relatively high degree of organizational cumulativeness. As showed in Figure 3, the main players were historically integrated semiconductor companies. Only during the early exploratory phase, there is some variety in terms of the organizations involved: together with TI, we find indeed two established conglomerates, earlier vacuum tube producers (i.e., Westinghouse Electric and RCA), and Data General, one of the first minicomputer firms, at that time a recent Digital Equipment's spin-off. During the decade from the mid-1970s to the mid-1980s, IMB dominated the exploitation of the microprocessor breakthrough. At that time, IBM was the most important computer company and IC manufacturer, and 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 subsequent decade was dominated by TI, which maintained an integrated structure until its recent decision to use foundry partners for 32 nm process technologies (LaPedus and Clarke, 2007). The main SoC advancements were generated by some of the most important US microprocessors companies including Intel, Advanced Micro Devices (AMD) and Motorola, while the developments concerning PSoCs were generated by Actel, a Silicon Valley company founded in 1985 and active in the market of PLDs. All patents selected by the CPM algorithm were generated by US companies, with the notable exception of the Italian-French STMicroelectronics (STM), which nevertheless patented with its US-based subsidiary. STM was formed in 1987 by the merger of state-owned companies SGS Microelettronica and Thomson Semiconducteurs, and is headquartered in Switzerland.

Figure 3. CPM

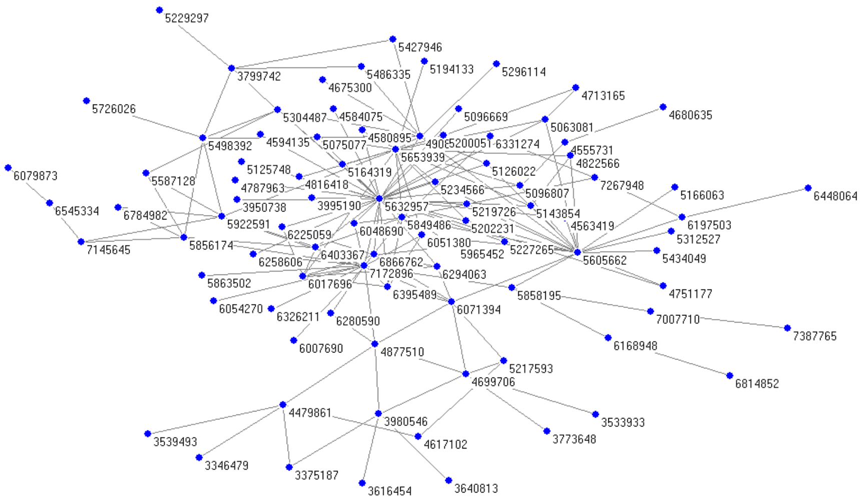


The CPM algorithm enabled us to identify, visualize and discuss the main direction of knowledge accumulation of the miniaturization trajectory, but ignored the variety of the research areas that grew complementarily. The Island algorithm, by identifying the main thematic clusters into the entire dataset, 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 the over 3,000 clusters of patents that 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 path and includes all CPM patents as well. Therefore, this Island (CPM Island) represents the body of knowledge most closely connected with the backbone of the miniaturization trajectory. The second Main Island is specialized on digital optical communications systems, where semiconductor devices, in particular light-emitting diodes (LEDs) and laser diodes, are used like transmitters. The third Main Island relates to microfluidics, which deals with the behavior, control and manipulation of 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 analyzed substances very expensive (e.g., Lab-on-a-chip). Other important Technological Islands concern with the development of single electronic components, especially memory devices, and on semiconductor process technologies (e.g., chemical-mechanical planarization techniques, mask manufacturing methods etc.). The remaining Islands regard the advancement of the different technological areas where semiconductors diffused over time, and include relative established fields like consumer electronics products and automotive applications, as

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

well as relative new areas of inquiry at the intersection with other science domains like optical communication technologies, microfluidics and medical devices. Figure 4 shows an example of a technological Island.

Figure 4. Main Island "Microfluidics



The Island algorithm maps the composition of the technological knowledge generated along the whole evolution 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). To overcome this limitation and detect the most recent developments of the miniaturization trajectory, we applied the Island algorithm to a reduced dataset, starting from 2000[13]. Table 1 shows the geographical and organizational distribution of patents selected by the Island algorithm. Grey rows show the results relating to the whole period considered (Technological Islands$_{1976\text{-}2008}$), while white rows refer to the most recent time period (Technological Islands$_{2000\text{-}2008}$). By looking at the total number of patents granted to firms from 1976 to 2008, we observe that US companies generated most of the contributions, followed by Japan and European countries, while SEA companies play a marginal role.

[13] We followed the same procedure used by Mina et al. (2007).

Table 1. Technological Islands, geographical and organizational distribution (%)[14]

	USA	JP	EU Countries	SEA Countries	Other Countries	No Assignee	TOT
Firms	70.7	16.5	10.5	1.1	1.3	-	100
	72.9	15.9	4.7	5.0	1.5	-	100
Research organizations and government agencies	77.5	8.6	4.3	2.7	7.0	-	100
	67.5	0.8	6.5	13.8	11.4	-	100
TOT	67.1	14.6	9.2	1.2	1.8	6.1	100
	69.5	14.3	4.6	5.3	2.0	4.2	100

(grey) Technological Islands$_{1976-2008}$ (white) Technological Islands$_{2000-2008}$

By analyzing more in detail these patents, we found that Japanese companies were prominent especially in the clusters relating to consumer electronics products and automotive applications, while contributed importantly also to the Technological Islands concerning electronic components and communication technologies. The main players were relatively established, diversified and vertically integrated electronics firms, including Hitachi, Mitsubishi, NEC, Toshiba, Matsushita, Sony and Canon. European companies were involved in almost all Technological Islands, but they played an active role only in the clusters concerning automotive applications, consumer devices 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 prevailed. IBM, ADM, Motorola, TI and Intel contributed to many clusters, especially to the CPM Island and semiconductor process technologies. Micron Technology dominated the Technological Islands concerning memory devices, Xerox was particularly active in developing MEMS applications[15], HP in microfluidic chips, and AT&T in the communication field. Biotech and life science companies were important players in the clusters relating to microfluidic and medical technologies.

As showed by Table 1, if we look at the most recent clusters of inventions of the miniaturization trajectory (Technological Islands$_{2000-2008}$), the geographical and organizational distribution of knowledge changes. In particular, we can see that while US firms preserve and consolidate their position, the contributions generated by Japanese firms slightly lessen and the technological advantage of European firms is considerably eroded by the emergence of SEA companies. By analyzing SEA patents, we found that the main players were the Korean business groups Samsung, Hyundai and LG, which focused especially on the clusters relating to consumer electronics products and communication technologies. The remaining SEA contributions came mainly from a number of companies based in Taiwan, including Genesis Photonics, Taiwan Semiconductor Manufacturing and Macronix International.

[14] The procedure to build this table is based on the address of the patent assignee listed on the patent and do not take into account ownership relations between organizations (e.g., mother- and daughter-firms, or mergers, acquisitions and split-ups). In the table, the upper-left cell, for example, shows that 70.7% of all firms engaged in all Technological Islands$_{1976-2008}$ are based in the US.

[15] 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.

Other relevant results that we obtained from the analysis of Technological $Islands_{2000\text{-}2008}$ regard the greater importance of the clusters concerning optical communication systems, SoC design challenges, and semiconductor sensor applications. Besides, we found an 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, Altera and Broadcom, and by the EDA company Cadence Design Systems. The contributions of such firms mainly focused on PSoCs and PLDs, 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 semiconductor firms including IMB, TI, ADM, STM, and Intel. Fablesses partially contributed to the fields of electronic components, IC testing, and communication technologies as well. The most active firms in these fields were Cirrus Logic, Cisco Systems, and Broadcom. Fablesses and other specialized companies are mostly located in the Silicon Valley.

4.2. Research organizations and government agencies

The CPM algorithm identified the backbone of the miniaturization trajectory, while the Island algorithm mapped all major specialized bodies of knowledge contained in the whole research space of the miniaturization trajectory. The Hubs and Authorities algorithm allows us to further explore the pattern of knowledge advancement by disclosing the core discoveries that laid the foundation of the miniaturization trajectory (Authoritative patents) and their best developments (Hub patents). Tables 2 and 3 report the ten highest ranked Hub and Authoritative patents.

Authoritative patents were generated in the 1980s, while Hub patents in the late 1990s. Both Hubs and Authorities deal with parallel computing systems[16] and focus 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 computational 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 research on parallel processors, by continuously pushing the frontier of computers processing capacity, emerged as the basic knowledge of the miniaturization trajectory. While Authoritative patents focus mostly on increasing the number of processors operating in parallel, Hub patents are 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" (Patent No. 5794059).

[16] 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).

Table 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

Table 3. Hub 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)

As showed in Table 2, four out of the ten highest ranked Authoritative patents were generated by some of the most prestigious US research universities including the Massachusetts Institute of Technology (MIT), the Johns Hopkins University, the Duke University, and the Purdue University. Military government agencies supported the realization of Authoritative Patents No. 4380046, 4523273 and 4720780[17]. As reported in the 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 Patent 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 the CPM Island as well (Patents No. 4079455, 4597080, 4720780). These contributions were generated in the 1980s by RCA, TI, and The Johns Hopkins University with the support of the Army, the Air Force, and the Navy, respectively. 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 defense 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 defense, aerospace, and supercomputers emerged in the CPM Island as well[18]. As indicated in Table 3, IBM alone was responsible of generating all Hub patents, showing to be the organization capable of developing at best the basic knowledge that laid the foundation of the miniaturization trajectory.

Further relevant information about the knowledge generated by research organizations and government agencies is provided by the analysis of Technological Islands. As showed in Table 1, US organizations were by far more active than their foreign counterparts in both the time periods here considered (1976-2008 and 2000-2008), although a slight decline can be observed for the most recent years. This decline seems to be caused, at least in part, by the dynamism of SEA research organizations. We also calculated the share of patents generated by US research organizations and government agencies on the total US patents selected by Technological Islands$_{1976\text{-}2008}$. We found that this share amounts to 12.2%, while the share of patents falling within the Government Interest class is 6.3%[19]. 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 completely covered by our dataset.

US research organizations were particularly active in the generation of those relatively new clusters of inventions at the intersection with other science domains where semiconductor components diffused, i.e., optical communication systems, microfluidics, mass spectrometry[20],

[17] Patents filed with the USPTO may contain a field labeled "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.

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

[19] 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 Technological Islands$_{1976\text{-}2008}$.

[20] 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

medical devices, and semiconductor sensors applications. The Stanford University and the Bell Laboratories played an important role in the clusters relating to optical communication systems, with a focus on laser systems. The University of Pennsylvania stood out in the clusters concerning microfluidics, while The Charles Stark Draper Laboratory and the California Institute of Technology focused mainly on mass spectrometry-related clusters. In the clusters on medical devices, the main contributions 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 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 agencies of those decades were the Department of Energy (DOE) and its predecessor (the Atomic Energy Commission), the Department of Navy, the Air Force, and the Army. Since the 1990s, the US government activity shifted towards the same clusters where research organizations focused (i.e., microfluidics, optical communications systems, medical devices, mass spectrometry, and semiconductor sensor applications). The major players were the Advanced Technology Program (ATP), the National Science Foundation, the Department of Navy, the National Institutes of Health, the NASA, the DARPA, and the DOE.

Compared to the US, the contributions of research organizations 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 (respectively) that emerged from Technological Islands$_{1976\text{-}2008}$. In Japan, the most active organization was the METI's Agency of Industrial Science and Technology (AIST), while the sporadic contributions of European organizations were mainly generated by the British Ministry of Defence, the French *Commissariat a l'Energie Atomique*, and the British Atomic Energy Authority. Finally, with regard to SEA countries, the share of patents owned by research organizations on the total patents granted to SEA countries is 16.2%[21]. In Korea, two main organizations emerged with important contributions in the clusters relating to communication technologies: the ETRI (Electronics and Telecommunications Research Institute) and the KAIST (Korea Advanced Institute of Science and Technology). In Taiwan, the main contributions were generated by the ITRI (Industrial Technology Research Institute) and focused on the clusters concerning electronic components and semiconductor process technologies.

5. Discussion

Table 4 outlines the results that have been illustrated in section 4. Overall, we found significant differences in both the characteristics of the main national organizations at play and their technological capabilities, as disclosed by the magnitude and the properties of the technological knowledge that these organizations generated along the evolution of the miniaturization trajectory.

[21] These data refer to Technological Islands$_{2000\text{-}2008}$, since data referring to whole period (1976-2008) are not significant for SEA countries.

Table 4. Outline of the main results

Network Analysis Algorithms	Knowledge Pattern	Knowledge properties	Technical problem	Prevailing geographical locations and organizational forms
CPM	Backbone	Cumulativeness	Testing and integration of microprocessor systems	US firms
Island	Major clusters of inventions	Specialization	Testing and integration technologies	US firms
			Microfluidics	US firms US universities and government agencies
			Communication technologies	US and JP firms US universities and government agencies
			Semiconductor process technologies	US firms
			Single electronics components	US, JP and EU firms
			Consumer electronics products	JP, US, EU and SEA firms
			Automotive applications	US, JP and EU firms
			Medical devices	US firms US universities and government agencies
			SoC design challenges	US firms
Hubs and Authorities	Core discoveries	Basicness	Parallel processors	US universities and government agencies US firms

First, compared to their counterparts in Japan and Europe, US universities and government agencies were by far more active. As showed by the list of the 10 highest ranked Authoritative patents and the results relating to Technological Islands (1976-2008), these organizations played a critical role in generating (or supporting the generation of) both the basic knowledge that laid the foundation of the miniaturization trajectory (i.e., parallel processors) and those relatively new specialized bodies of knowledge underlying the market segments where semiconductor components diffused over time (i.e., optical communication systems, microfluidics, and medical devices). Earlier historical studies have highlighted the importance of US universities and federal R&D funding in determining the US strength in the semiconductor industry (e.g., Dosi, 1984; Macher et al., 1998; Mowery and Nelson, 1999). Our results, on the one hand, provide empirical evidence supporting that argument, and, on the other hand, offer a finer grained analysis of the role these organizations played during the evolution of the industry. Our data concerning the most recent evolution of Technological Islands (2000-2008) also show that, differently from Japan and Europe, SEA countries are following a path which importantly relies on the contribution of public research.

Second, our results provide evidence that a relatively stable and small group of large and established firms were predominant against smaller and new firms, both in the US and elsewhere. However, when we analyzed the most recent evolution of Technological Islands (2000-2008), we found an increased importance of Silicon Valley-based fables and EDA companies. These firms played an active role especially in the specialized bodies of knowledge concerning with the SoC design challenges, focusing on those developments that are characterized by higher flexibility, lower sunk costs and faster development times (i.e., PSoCs and PLDs). These results seem to be consistent with Somaya and Lyinden (2003), who suggest that the process of vertical specialization spurred by the emergence of SoC technologies is associated with an increased dynamism of smaller and specialized firms. However, we found that compared to fabless and EDA companies, foundries, IP providers and other networked firms analyzed by Somaya and Lyinden (2003) played a minor role. We also found little evidence supporting the increased importance of Taiwanese smaller design companies. This seems to confirm Chang and Tsai (2002), who found that Taiwan did not attempt to challenge the US technology leadership in IC design, but rather focused on being a superior quick follower, through knowledge assimilation and utilization.

Third, compared to their foreign competitors, US firms largely dominated the generation of new technological knowledge over the whole time period considered in this study. The main US players were relatively integrated semiconductor firms, together with some ‘‘systems’’ manufacturers like IBM. As showed by the evolution of the CPM path, these firms pursued a strategy that at first bet on the last radical innovation of the industry (the microprocessor) and later focused on the cumulative solution of the testing challenges arising from the design of increasingly integrated microprocessor systems. Besides, these same firms played a dominant role in many important specialized bodies of knowledge (Technological Islands 1976-2008), including semiconductor process technologies and electronic components, as well as in the most recent developments of the miniaturization trajectory concerning the SoCs design challenges (Technological Islands 2000-2008). As emerged from the list of the 10 highest ranked Hub patents, IBM alone was responsible of generating all the most important developments of the basic knowledge that laid the foundation of the miniaturization trajectory (i.e., integration of parallel processors).

Conversely, in Japan and European countries the main players were relatively integrated and diversified electronics firms. Both Japanese and European firms followed a strategy markedly different from that of US companies, largely focusing their efforts on generating those specialized bodies of knowledge relating to consumer electronics products and automotive applications (Technological Islands 1976-2008). Although these firms expanded their competences to other specialized bodies of knowledge as well (i.e., electronic components and communication technologies), they generated here only part of the relevant knowledge. Compared to European firms, Japanese companies showed higher technological capabilities, but gained an advantage over US firms only in consumer electronics technologies. Our data relating to the most recent evolution of Technological Islands (2000-2008) show that SEA firms, which were mostly Korean electronics companies, are following the same strategy of specialization in consumer and communication technologies that was pursued by Japanese and European companies. These data also show that the emergence of Korean firms importantly eroded the technological advantage of European firms, which in the most recent years experienced a deep decline in their technological capabilities. Conversely, US and Japanese firms were able to preserve their areas of competitive advantage and there is also some evidence that US firms consolidated their position.

These results are broadly consistent with earlier historical studies that have analyzed the evolution of national competitive advantage in the semiconductor industry (Langlois and Steinmueller, 1999; 2000). Langlois and Steinmueller (2000) found that the US resurgence during the 1990s was importantly determined by a renewed focus of US semiconductor firms on what had long been their distinctive capabilities in higher margin, design-intensive chips, especially microprocessors and related chips, where innovation is a critical factor of competition. The same authors (Langlois and Steinmueller, 1999) have highlighted the strength of Japanese electronics companies in consumer electronics products and the relative success of European firms in consumer and automotive applications. Our results show, in addition, that by focusing on the design of microprocessor systems, US semiconductor firms maintained the command over the most important stream of knowledge accumulation that emerged along the whole evolution of the miniaturization trajectory. Moreover, our results suggest that, differently from their foreign competitors, US firms expanded their knowledge bases well beyond their distinctive areas of competitive advantage, including also areas where they do not have a competitive advantage, like for example memory devices[22].

There are nevertheless organizations that fall outside of the patterns discussed above and implemented strategies that "bucked" the general trends observed. Surprisingly, we found that, besides universities, also a small number of US aerospace, defense, and supercomputer companies played an active role in the 10 highest ranked Authoritative patents. By pointing at the generation of the basic knowledge on parallel processors that laid the foundation of the miniaturization trajectory, these firms pursued a strategy markedly different from that of their US and foreign competitors. Given both the distinctive characteristics of these firms and the considerable involvement of US public agencies as sponsors and customers for parallel processors technologies (Mackenzie 1991, Williams 1985, Metropolis and Nelson 1982), these results seems to suggest that US military demand played an important role in shaping the strategy of these firms. If so, we should conclude that US military demand played an important role not only during the early years of the industry, as previous studies have highlighted (Malerba, 1985; Langlois and Steinmueller, 1999), but even during its (relatively) more recent evolution (i.e., the time period covered by this analysis). The military character of the US agencies that supported some of the other highest ranked Authoritative patents further corroborates this conclusion.

A second surprising result relates to the behavior of STM. There seems to be evidence indeed that this Italian-French semiconductor firm bucked the general declining trend experienced in the most recent years by European firms. As showed by the presence of STM's patents in both the main path of knowledge accumulation of the miniaturization trajectory and many connected specialized bodies of knowledge (i.e., electronic components, semiconductor process technologies and SoC design challenges), the strategy pursued by STM was different from that of the other European companies and it was for many aspects similar to that of US semiconductor firms. It should be noted however, that in pursuing this strategy STM often used its US-based subsidiaries.

The findings discussed so far have to be considered with some caution, due to the limitations of using patents and patent citations as measure. First, patent citations may not perfectly reflect the knowledge bases that organizations rely on. For example, Alcacer and Gittelman (2006) found that the magnitude of citations added by USPTO patent examiners is high and raise concerns about the unknown noise that such citations, which typically are not separately reported, can add to the data. In response to these concerns, Barbera et al. (2011) have recently tested patent citations methods, and in particular the network citation methods used in the present analysis, showing their validity for studying technological evolution. This seems to suggest, that, at least for what concerns the analysis of technological evolution, the bias introduced by examiners' citations is not necessarily bad.

Second, the extent of technological capabilities is not fully revealed by patenting activity. It is indeed well known that not all inventions are patentable and not all patentable inventions are patented, because different strategies are used for protecting intellectual property and competitive advantage (see for example Arundel and Kabla, 1998)[23]. Even more important for this analysis, patents are often used for strategic objectives and patent strategies differ both over time and across firms, even within the same industry or technological area (Hall and Ziedonis, 2001; Ziedonis, 2004). Due to the rapid pace of technological change and short product life cycles, firms in the semiconductor industry tend to rely more heavily on lead time, secrecy, and manufacturing or design

[22] The market for memory device was dominated by Japanese firms early on, and by Korean firms later (Langlois and Steinmueller, 1999).

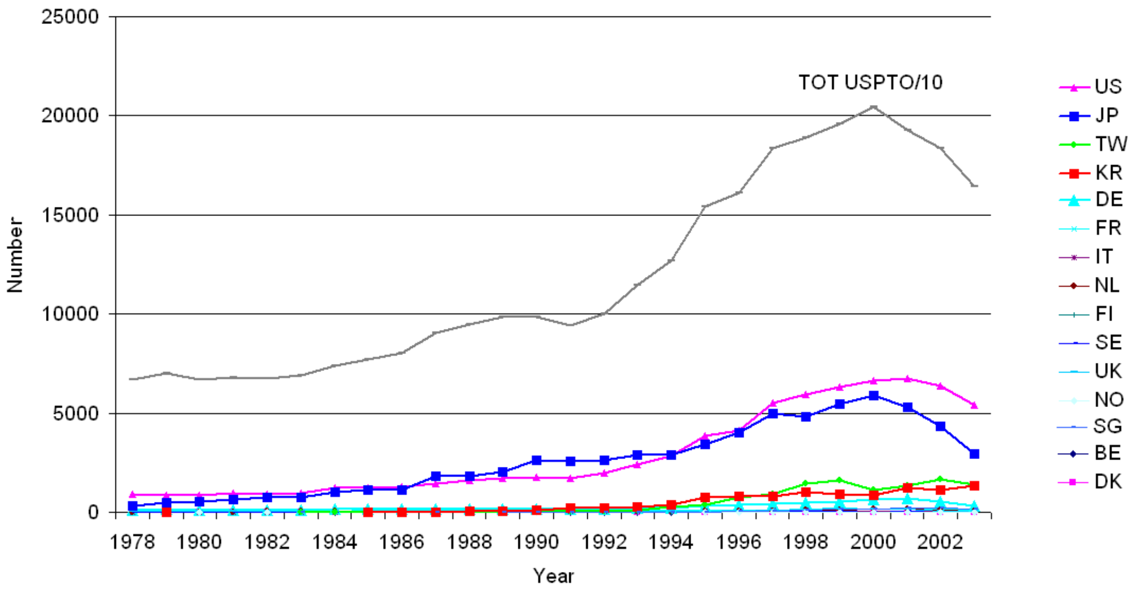
[23] See Pavit (1985), Griliches (1990), Jaffe and Trajtenberg (2002) for a discussion on the usage and limitations of patent documents.

capabilities than patents to profit from innovation (Hall and Ziedonis, 2001). Nonetheless, the number of US semiconductor-related patents has risen sharply since the early 1980s, exceeding the overall increase in US patenting (Kortum and Lerner, 1998). In exploring this apparent paradox, Hall and Ziedonis (2001) found that the surge in semiconductor patents was not accounted for neither by increases in R&D spending (the propensity of semiconductor firms to patent has also raised) nor by technological/managerial improvements. Rather, the primary reason was found in a more aggressive patenting by US semiconductor large manufacturers (capital-intensive firms), which responded in a strategic way to the 1980s strengthening of US patent rights, i.e., by building larger portfolios of their own ‘‘legal rights to exclude’’ with the aim of reducing the holdup problem posed by external patent owners and negotiating access to external technologies on more favorable terms. By analyzing the behavior of a sample of 67 US semiconductor firms, Ziedonis (2004) found that a firm's patenting strategy depends on the fragmentation of its markets for technology and on the firm's own level of investment in technology-specific assets. More in particular, Ziedonis (2004) found that capital-intensive firms patent more than five times as aggressively in response to average levels of fragmentation in markets for technology as firms of average capital-intensity.

Although our data do not provide any direct evidence on neither firms patenting strategies nor the reasons behind differing patenting strategies, the findings discussed above have important implications for our analysis and suggest that our results may be to some extent biased by the different patenting strategies pursued by organizations. This is particularly important for the results relating to the dominance of US large semiconductor firms against smaller US design companies, which, according to Hall and Ziedonis (2001), did not engage in the same “patent portfolio races” as US capital-intensive firms and, according to Ziedonis (2004), patent less aggressively than capital-intensive firms in response to equal levels of fragmentation in markets for technology. Unfortunately, we do not have comparable studies on the patenting strategies pursued by non-US firms that patented at the USPTO. As a consequence, we are not able to discuss if our results concerning the relative dominance of US firms against non-US firms has been affected too by the differing patenting strategies at play.

Finally, in absence of a unified global patent database, this study has used the UPSPTO, the most representative database. Although this may have biased to some extent the results of our analysis toward US organizations, still patenting in the US market is important for foreign countries in order to protect areas of competitive advantage, and US patenting activity by foreign organizations remains a good measure of the technological capabilities of foreign countries (Pavitt, 1985). Moreover, as Figure 5 shows, the patenting activity of the USPTO seems to reflect very closely the pattern of industrial leadership in the semiconductor industry: the early US dominance, the Japanese challenge during the 1980s, the 1990s US resurgence, the rise of SEA countries, as well as the relative peripheral role of European countries.

Figure 5. Semiconductor patents granted by the USPTO by priority year at the national level



Source: Eurostat

6. Conclusion

Using an original dataset of patents and three algorithms for the analysis of citation networks, this article mapped the pattern of technological knowledge underlying the long-term evolution of the miniaturization trajectory. We first identified three different dimensions of the knowledge pattern – the core discoveries, the backbone and the major clusters of inventions of the miniaturization trajectory – and characterized them in terms of distinctive knowledge properties, namely basicness, cumulativeness and specialization. We then analyzed the geographical and organizational distribution of the knowledge pattern, disclosing the main national organizations at play and their technological capabilities, as revealed by the magnitude and the properties of the technological knowledge that these organizations generated over time.

The results provide evidence for significant differences in both the characteristics of the main national organizations and their technological capabilities. First, compared to their counterparts in Japan and Europe, US universities and government agencies were by far more active and played a critical role in generating both the basic knowledge that laid the foundation of the miniaturization trajectory (i.e., parallel processors) and the specialized knowledge underlying those relatively new market segments where semiconductor devices diffused over time (i.e., optical communication systems, microfluidics, and medical devices).

Second, a relatively stable and small collection of large and established firms were predominant against smaller and new firms, both in the US and elsewhere. However, in the US the main players were relatively integrated semiconductor firms, together with some “systems” manufacturers like IBM, while in Japan, Europe and SEA countries integrated and diversified electronics firms largely prevailed. As discussed to a greater extent in section 5, the dominance of US large manufacturers against smaller design companies may be due, at least in part, to the different patenting strategies that these firms pursued as response to the 1980s strengthening of US patent rights (see Hall and Ziedonis, 2001; Ziedonis, 2004). Moreover, we found evidence for a more recent dynamism of Silicon Valley-based fables and EDA companies, which seems to be linked to the process of vertical specialization spurred by the emergence of SoC technologies.

Third, compared to their foreign competitors, US firms dominated the generation of new technological knowledge over the whole time period considered. By betting on the last radical innovation of the industry (i.e., the microprocessor) and focusing on the cumulative exploitation of the technological opportunities contained in such innovation (i.e., integration of microprocessor systems), US semiconductor firms maintained the command over the most important stream of knowledge accumulation that emerged along the whole evolution of the miniaturization trajectory. Besides, these firms accumulated higher technological capabilities in important specialized bodies of knowledge that grew complementarily (e.g., semiconductor process technologies, memory devices, SoCs design challenges). Japanese and European electronics companies followed a strategy markedly different from that of US firms, largely focusing their efforts on generating specialized knowledge relating to consumer electronics products and automotive applications. Japanese companies showed higher capabilities than European firms, but gained an advantage over US firms only in consumer electronics technologies. Our results also show that the emergence of Korean electronics companies importantly eroded the technological advantage of European firms, which, despite some exceptions, in the most recent years experienced a deep decline in their technological capabilities. The outlier behavior of a small number of US aerospace, defense, and supercomputer companies, which pointed at generating the basic knowledge of the miniaturization trajectory, suggests that US military demand played a role in shaping the strategy of these firms. The US agencies that supported the generation of this basic knowledge also have a military character.

Although these findings are subjected to a number of caveats (see section 5), they have important implications for the literature on the sources of leadership in the semiconductor industry. First, they provide empirical evidence that US universities and federal R&D funding were, and still are, an important source of technological leadership, while offering a finer grained analysis of the role they played during the evolution of the industry. We also show that the poor performance of universities and government agencies in Japan and Europe contributed to determine the relative weakness of these countries compared to US. Second, as discussed in more details in section 5, the technological areas where national firms accumulated their capabilities largely correspond to their distinctive fields of competitive advantage, as analyzed by previous studies (Langlois and Steinmueller, 1999; 2000). This suggests that in the long-term competitive outcome is highly rooted in technological capabilities that national firms are able to generate and accumulate over time. However, we also found that, compared to their foreign competitors, US firms expanded their knowledge bases well beyond their characteristic areas of industrial strength, including also areas where they do not have a competitive advantage, like for example memory devices. Third, it appears that US military demand played an important role not only during the early years of the industry, as previous studies have highlighted (Malerba, 1985; Langlois and Steinmueller, 1999), but even during its (relatively) more recent evolution (i.e., the time period covered by this analysis).

More in general, this article shows for the first time that investigating the dynamics of technological knowledge through citation network methods can be a useful tool for highlighting the sources of knowledge generation and the technological capabilities of organizations. Rather than selecting a sample of organizations and analyzing their patent portfolio, as it is common in the literature (see for example Patel and Pavitt 1997), this study started by mapping the knowledge pattern of a technological trajectory, allowing the identification of the main organizations at play and their capabilities on the basis of the knowledge that organizations generated along this pattern. Moreover, this approach allows detailing organizations' capabilities taking into account for the first time also the properties of the knowledge involved.

Our findings suggest the following policy implications. First, Japan and European countries may benefit from strengthening their university research and ***system of public laboratories***. Discussing the specific characteristics of different scientific systems and the connected policies supporting their strength is beyond the scope of this article and has been the focus of other studies (see for example

Dosi et al., 2006; Bonaccorsi, 2007). However, with respect to the case of semiconductors, here we suggest that policies should put more emphasis on stimulating the potential of public research for generating new knowledge in those technological areas at the intersections between different science domains (e.g., physics, biology, medicine) where semiconductor components diffused in the most recent years and where it is expected that they will diffuse even more in the forthcoming years, e.g., medical devices, nanotechnologies, photovoltaics. In these fields, where the technological opportunities created by basic and explorative research are particularly important, public research can play a unique role. Second, active sectoral-specific industrial policies may help European firms to close the technological gap they cumulated in the recent years. European countries are a heterogeneous actuality and devising specific public policies for the whole European context would require deeper and more situated analyses. Here, we limit ourselves to suggest a number of general policies that may be considered. These include policies supporting the acquisition and assimilation of external knowledge, as well as the diffusion and exchange of technological knowledge, for example through technological transfer agreements, among European firms and with foreign firms, or the creation of technological infrastructures like technological parks. Polices supporting firms capabilities in generating new technological knowledge may be important too and may include policies supporting university spin-offs and university-industry R&D projects, procurement policies for selected and broadly-targeted technologies, and R&D public projects based on peer review assessment of merit and whose results are widely diffused within the industry. As before, it seems to be important focusing policies on the new and emerging areas of application and experimentation of semiconductors, where technological opportunities are supposed to be high. Third, this analysis seems to provide evidence that, even in a relative established paradigm like semiconductors, government demand can play an important role in shaping the priorities of industrial firms, motivating them to explore and invest in the most complex and uncertain areas of inquiry, where performances matter more than costs. This is even more important for emerging technological areas and potentially new technological paradigms, especially when there is a collective interest in their development, e.g., sustainable technologies. In this respect, government policies aimed at creating or stimulating market niches willing to pay a significant premium for some superior characteristics of products may be particularly useful (see for example Kemp, 1994; Kemp et al., 1998).

This study has of course limitations, which provide opportunities for further research. To begin with, this is a single technology case study and its results should be generalized with care. However, the methodology here developed yields an interesting potential for application in other high-technology industries. Furthermore, even in high-technology industries, industrial leadership depends on other factors than technological strength, including firms' capabilities to exploit internal and external knowledge, investment and manufacturing capabilities, product mix or production outsourcing and market-structural factors. While this article has tried to discuss on the basis of the existing literature some connections between technological capabilities and competitive outcome, further research is needed to show how different technological capabilities create diverse sources of competitive advantage and affect competitive outcome. Finally, further research is also needed to understand how the dynamic evolution of the different systems of innovation shapes and interacts with the observed differences in organizations' technological capabilities.

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Appendix

Table 1. Ciatation Network, most important patents

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)

Table 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	International Business Machines Corporation

			level sensitive logic system	(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)

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