

On the creation and distribution of knowledge in microelectronics

Margherita Balconi, Università degli Studi di Pavia, Italy
Alfonso Centuori, Global Communication Devices, North Andover (MA), USA

This paper investigates how the microelectronic community responded to the challenges set by a very high level of knowledge complexity and a frantic pace of innovation. In particular it explores: i) the drive towards standardization of process technologies, global coordination and knowledge sharing, to go along a well defined trajectory of innovation without wasting resources; ii) the role of academic research in the applied microelectronic engineering field and the connection with industrial research; iii) the management of new knowledge by industry; iv) the division of innovative design labour and the role and limits of the growing market for design information. Overall, the various aspects of knowledge creation and distribution which characterize the field are examined.

1. Introduction*

The pace of improvement of semiconductor devices since the invention in 1959 of the integrated circuit (IC) has been astoundingly rapid. Following Moore's law (stated in 1965) the number of transistors integrated on a given area of silicon doubled about every 18 months. At present, millions of transistors are integrated on an IC and entire systems with many functionalities are built on a single die. These outcomes are associated with increasing levels of knowledge complexity. The task of creating new knowledge and innovating at the pace required to keep up with Moore's law has been increasingly demanding and it wound up with exceeding the resources and capabilities of even the largest companies.

This paper is about the changes driven by the efforts of the microelectronic community to carry out the task of very complex knowledge creation, in the context set by the availability of ICTs. It attempts to give a global account of the articulated response that emerged, in part as a result of conscious and cooperative efforts undertaken by the community and in part as the unplanned outcome of decentralized entrepreneurial decisions.

The changes concern: 1) the emergence of new institutions intended to foster cooperation at the worldwide level (such as International SEMATECH and the International Technology Roadmap for Semiconductors), 2) the re-orchestration of the division of roles among universities, large firms and start-ups with regard to the task of knowledge creation and, finally, 3) the deepening of the division of innovative labour among firms.

As to the first point, section 2 describes the negotiated management of the challenge set by the need to move rapidly along the technological trajectory of miniaturization and increasing density. Knowledge sharing, coordination of technological targets and schedules,

* The authors would like to thank the many persons (entrepreneurs, experts, managers, technical staff, university professors of the microelectronic community) who kindly collaborated, accepting to go through our time-consuming, often repeated, open interviews. In particular, we thank Russell Cyr, Geoff Dawe, Ken O, Stan Reible, Giovanni Cesura, Clara Colombo, Matteo Conta, Rinaldo Castello, Franco Maloberti, Federico Montecchi, Francesco Svelto, Guido Torelli, Giuseppe Zocchi. The usual disclaimers apply.

intense know-how trading were functional to face this need. The standardization of technologies achieved has been particularly important, since it was the basis for de-linking design from manufacturing. ICTs were crucial to support highly codified connections between manufacturers and their distant clients.

Section 3 discusses the respective roles of the academy and industry in conducting research on circuitry, systems and in general on the new applications made possible by increasingly miniaturized devices. Research on these topics is typically applied in nature, and falls within the realm of the “sciences of the artificial”, namely “purposive goal-directed activities, whose explicit design orientation seems to exclude them from the usual definition of basic research (which involves the quest for fundamental understanding)”(Rosenberg and Nelson 1994). The analysis of the nature of research conducted by both institutional actors is useful to shed light on the (self-interested) choices made by industry with respect to the management of research results (dissemination *vs.* appropriation). The exchange which takes place in the collaboration between university and industry is also examined.

In section 4 bibliometric data are presented that confirm the increasing intensity of the interconnections between the academic and the industrial microelectronic communities.

In section 5 the focus is shifted to industry and to the division of roles among start-ups and established firms with regard to the task of creating fully engineered design knowledge on which marketable products are based (both tangible and intangible ones). It is discussed how the wide potential for variety of experimentation drove (and continues to drive) the emergence of an entrepreneurial segment of the industry. Finally, the attention concentrates on the division of innovative labour which was spurred by the multiplication of functionalities to be assembled on systems-on-chips. It is shown how the scope of the market for design information, which is still growing in the Internet virtual space, is however limited to simple design modules, since complex modules need the provision of the tacit knowledge of their creators, in order to be understood.

2. Towards a collective response to the challenge of technological complexity: coordination, standardization, and horizontal know-how sharing and trading

In the fifties and sixties much of the fundamental research that brought to the emergence and early growth of the semiconductor industry was performed in the large U.S. laboratories of AT&T, GE, and IBM. However, already in the seventies they started to shift their focus on near-term corporate goals and applied research (Macher, Mowery and Hodges, 1998). A reinforcement of the U.S. sectoral system of research based on a novel pattern was set in motion at the end of the seventies by the perception by the American semiconductor industry of its loss of dominance at the global scale. In fact when, at the end of the seventies, Japanese companies managed to capture more than 40% of the U.S. market for 16 Kbit DRAMs and even to gain a positive trade balance with the U.S in integrated circuits (1980), the U.S. industry had to become aware that its dominance was challenged, and that it had to find a new way to strengthen its technological capabilities. Then the American industry initiated and organized a cooperative effort to sustain long term research, no longer depending on the glorious traditional large laboratories.

Already in 1977, the Semiconductor Industry Association had been created, to gather information on the industry and to develop mechanisms for addressing industry issues with the government. Within the SIA in 1981 was proposed the creation of a "semi-conductor research cooperative" to assure continued U.S. technology leadership in the face of the growing competition with Japan. Following this, in 1982 the Semiconductor Research

Corporation (SRC) ¹ was established, a consortium of numerous companies and government agencies committed to planning, managing and funding programs of pre-competitive, long-term semiconductor research to be conducted at leading universities and research institutions in the United States². Some years later, in 1987, the Department of Defence, worried about the repercussions of the decline of the industry, fostered some new action. This led to the creation of a consortium called SEMATECH (SEmiconductor MANufacturing TECHnology) by fourteen U.S.-based semiconductor manufacturers, whose aim was to develop cutting-edge process technology. Austin, Texas, was chosen as home to SEMATECH and the site of a large-scale fabrication facility which began operations in 1988. In the same year the government started funding the initiative. In a second phase, its mission was reoriented to improving the capabilities of domestic equipment suppliers through cooperation and leveraging federal resources³.

The recovery of the American semiconductor industry could be accomplished in about a decade, and already in 1992 the U.S. firms had regained the leadership in world chip sales, with a 44% share of global revenues, for the first time since 1984. Between 1994 and 1995 SEMATECH's Board made decisions to adapt the consortium to operate without federal funding after 1996, while the Congress was getting more sceptical at assisting a sector which had clearly recovered⁴.

The recovery of the industry, however, did not lead to relax cooperative efforts. At the contrary, in the middle of the nineties a point was reached whereby going along the technological trajectory of miniaturization and increasing integration of transistors in the dies and scaling of wafer size to increase productivity and lower production costs involved a degree of complexity, costs and risks that were very difficult for single firms to manage. To continue the path and to further expand the markets captured by the industry, it was necessary to maintain and further develop an intense cooperation. The challenge this time did not come from a competitor, but from nature, and defied all world competitors, generating the incentive to realize *a world wide technical and scientific cooperation*.

A significant step in this direction can be traced at the end of 1994, when SEMATECH participated in an international summit in Tokyo aiming to seek an agreement on next-generation wafer size. The agreement was reached on the 300 mm size. Immediately later, the International 300 mm Initiative (I300I) was formed (in 1995), as a subsidiary of SEMATECH, with seven non-U.S. companies and six U.S. companies cooperating on 300mm tool standards and specifications. In 1997, I300I and J300 (the Japanese led 300 mm development effort) signed the Global Joint Guidance Agreement to provide information on equipment configuration and factory systems to the global supplier community and to identify the 300 mm standards requirements of global device makers.

¹ See www.srs.org. Since it was established in 1982, SRC has funded more than \$500 million in research contracts.

² In 1982 the Microelectronics and Computer Corporation was founded as well, a for-profit organization conducting research also on semiconductors, but mainly devoted to research on computers.

³ On the origin and evolution of SEMATECH see Langlois and Steinmuller (1999, pp.63-64). In particular, according to them, the attempt to bring such a large number of firms to fully share process technology know-how, which was typically privately appropriated by firms, proved unsuccessful "because of problems of appropriability and proprietary information", and this led to reorienting SEMATECH mission. See also Katz and Ordover (1990).

⁴ In the period 1987-1996 SEMATECH received over \$ 850 million in dues from its members and roughly the same amount in matching funds from the U.S. Defence Advanced Research Projects Agency (DARPA). See Ham, Linden and Appleyard (1998).

This experience can be considered the first fully *global standardization effort* of technologies, and it marks a significant change both from the national competitiveness driven policies of the former period and from “going it alone” attitude of firms in the previous wafer transitions (as Ham, Linden and Appleyard, 1998, put it).

In 1998 five of the international companies participating in I300I (Hyundai, Philips, STMicroelectronics, Siemens, and TSMC) opted to participate in more of the consortium's programs through a subsidiary called International SEMATECH, and then ultimately made the decision to join SEMATECH as full members. In recognition of its global membership base, SEMATECH renamed itself International SEMATECH⁵.

It must be recalled that in the 1990s globalisation was proceeding rapidly also as a consequence of firm competitive strategies, as many chip manufacturers and their suppliers established manufacturing or assembly facilities in multiple regions of the world. Furthermore, alliances⁶, joint ventures, and many forms of cooperation were established among semiconductor manufacturers as well as among equipment, materials, and software suppliers at the world-wide level.

Limiting here the attention to global coordination in the domain of technological and scientific advancement, the main pillar of it became the construction of an international technology roadmap, a collectively built framework directing firms’ efforts to proceed along the technological trajectory.

It is worth mentioning that already in 1992 the SIA had coordinated the first efforts directed to give rise to what was originally *The National Technology Roadmap for Semiconductors (NTRS)*⁷. The *NTRS* provided a 15-year outlook on the major trends of the semiconductor industry. As such, it was a good reference document for all semiconductor manufacturers, suppliers of equipment, materials, and software and offered clear targets for researchers. Adapting to the new global environment, in 1998 the SIA at the World Semiconductor Council invited Europe, Korea, Japan and Taiwan (through their semiconductor industry associations) to cooperate to the creation of an *International Technology Roadmap for Semiconductors (ITRS)*, in consideration of the fact that a Roadmap that provides guidance to the whole industry would benefit from inputs from all regions of the world that have important activities in the field.

Since its inception, a basic premise of the Roadmap has been that continued scaling of microelectronics would further reduce the cost per function (averaging ~25% per year) and promote market growth for integrated circuits (averaging ~17% per year). Thus, the Roadmap has been put together in the spirit of a global industry challenge—essentially: “Which technological targets must be met for the industry to continue to stay on Moore’s Law and to collectively profit by the above mentioned trends?” .

ITRS provide a reference document of requirements, potential solutions, and their timing and a forum for international discussion, cooperation, and agreement among the leading semiconductor manufacturers and suppliers of equipment, materials, and software, as well as researchers from university, consortia, and government labs. Starting with this

⁵ Currently also some European and Israeli Universities are supported by International SEMATECH, besides American ones.

⁶ Macher, Mowery, Hodges (1998, p.118-20) note that US semiconductor firms were among the first U.S. high technology firms to pursue extensive alliances with foreign firms and that the expanded support for U.S. university research by foreign firms represents another form of growing international collaboration.

⁷ A *National Technology Roadmap* of requirements of the semiconductor industry and possible solutions was generated also in 1994 and 1997.

document as a common reference and through cooperative efforts among the various ITRS participants, the challenge is faced to cooperatively organize and fund a significant part of precompetitive R&D investments needed to generate new technological and scientific knowledge. The industry has thus reached a level of cooperation and standardization of technologies at the worldwide level which has no precedent⁸. The dominance of CMOS⁹ manufacturing technology was a solid foundation to the standardization drive.

Naturally, collaboration worldwide does not exclude that the most important programs of long run research are carried out at the level of countries or groups of countries, since public funding is usually organized at this level. At the country level, fundamental research has become the province of universities and public labs, and public funding of academic research is now usually matched by industry funds. As clearly put by SIA (2002):

“America’s semiconductor companies invest over \$10 billion per year in research and development. Because of the long time horizon and tremendous risks, a single company can rarely afford the cost of fundamental or basic research. As a result, fundamental research is largely performed at America’s research universities. While SIA member companies and other high technology companies have extensive, multi-million dollar programs to support university research, the Federal government is still the primary source of funds for basic research”.

In 1998 a new ambitious program of cooperation between university, industry and the government, the Focus Center Research Program (FCRP), was launched by the SIA, members of the U.S. semiconductor equipment, materials, software and services industries and the Department of Defence (DoD), represented by Defense Advanced Research Project Agency (DARPA) ¹⁰. The objective of the creation of a nationwide multi-university network connected by six Focus Centers is to expand pre-competitive, cooperative, long-range, applied microelectronics research at U.S. universities, in order to deal with industry needs that have been identified in the International Technology Roadmap. Over a 10-year period, the program is expected to channel more than \$600 million into the nation's research universities to study new methodologies in designing, testing and connecting microchip components.

In Europe, within the EUREKA framework, three industry-driven pan-european multi-projects programs followed each other, JESSY (1989-1996), MEDEA (1997-2000) and MEDEA+ (2001-2008). Their common objective is to strengthen the global competitiveness of the European microelectronics industry through R&D cooperation along the supply chain. These programs are financed by industry and research institutes with financial support from national public authorities and the European Union. They associate semiconductor manufacturers, their suppliers, system companies and design houses, private research

⁸ According to Ham, Linden and Appleyard (1998, p.155) “the semiconductor industry appears to be unique in the extent to which leading manufacturers are now working together world-wide to establish uniform standards for manufacturing technologies”. Moreover, the need to share R&D in the “precompetitive domain” is stated quite often both in SIA documents and in the ITRS.

⁹ As Langlois and Steinmuller explain (1999, p.44) by 1983-1984 CMOS became “the clear technological choice for almost all applications” and by the mid nineties it was responsible for 80% of IC production value.

¹⁰ Funds (by industry and the DoD) for the Focus Centers and participating universities provide salaries for students and faculty, along with equipment and upgraded facilities. A not-for-profit subsidiary of the SRC, the Microelectronics Advanced Research Corporation (MARCO) was chartered with the establishment and management of the FCRP on behalf of industry participants and DARPA. The Focus Centers themselves are "virtual" in that they consist of multiple universities. This allows for tapping the best expertise at a number of institutions in order to build the greatest overall capability in a particular technology area. The semiconductor industry funds should offset some of the recent federal cutbacks in technology research spending.

institutes and the academic world¹¹. This co-operation helps participants to share know-how and speed-up projects, while reducing costs and risks of innovative research. In particular, participating to the programs, the three main European semiconductor manufacturers, Philips Semiconductors, STMicroelectronics and Siemens Semiconductors (today Infineon Technologies) decided to cooperate on the most advanced research topics, together with universities and independent laboratories (which are mainly public). This cooperation is deemed to have been crucial for Europe's microelectronics industry in "reducing and in some areas closing" (Lucchini 1998) the gap in key technologies with the global competitors from the U.S. and Asia.

Like North American research programs, the research objectives of MEDEA+ are expressly in line with the ITRS.

An important aspect to note, which originates in the tradition and culture of the large labs of the fifties and sixties, is the high propensity of semiconductor firms to publish in scientific and technical journals. We shall come back to this point later. Suffice it to say here that the contribution of firms to the stock of open knowledge continued to be important over time and did involve an increasing number of firms, more and more in the form of co-authored articles by researchers of cooperating institutions. Moreover, as usual in most sectors, international conferences are important occasions whereby firms put the results of researches into the public domain.

However, this picture of (*pre-competitive*) negotiated standardization and openness, common definition of technological targets and their timing is not the whole story, since semiconductor producers are competitors in the supply of manufacturing services and as such need to leverage a proprietary know-how. Before focusing on this side of the story (*competitive appropriation*), a crucial aspect to consider is the effect of standardization of manufacturing technologies in enabling the de-linking of chip manufacturing from the designing of circuits. In fact specialised designers (and especially the so called fabless companies, namely companies with no fabrication facility, which outsourced manufacturing and sold finished chips) could emerge since, due to technological standardization, designs are almost fully "technology independent", in the sense that the chips designed can be produced with minor design modifications¹² by most chip manufacturers. Thus low transaction costs do not hinder vertical specialization in the supply chain and, along with (and complementary to) specialised designers, specialised semiconductor manufacturers have emerged, mostly located in Taiwan and Singapore, which sell manufacturing services to the former.

This logic of specialization and separation of the business of manufacturing from that of design has reshaped the economics of the whole industry and led to a clear division of highly knowledge intensive tasks among the various players (foundries and fabless companies), or

¹¹ MEDEA+ 220 partners include major microelectronics manufacturers, systems houses, SMEs, universities and institutes from 17 European countries. More precisely, 36% of the partners are small companies, 32% are large companies, 32% are research institutes and universities (see www.medea.org).

¹² Very briefly, we must recall that designing is carried out through three subsequent phases. The first step defines the functional block, the second the circuit model and the third derives the physical layout of the device from the second. Whereas the first two steps are *inherently technology independent*, the accomplishment of the third one requires the so called "design rules" of a specific foundry. If the design rules of different foundries were highly specific, designers would be locked in with a certain manufacturer and transaction costs would be relevant. The similarity of design rules of different foundries due to standardization, by eliminating this problem, facilitates vertical disintegration. However, freedom from lock-in does not imply that fabless companies frequently switch among various manufacturers, since they rather establish long run relationship with a preferred one.

between the different parts of the same integrated players (manufacturing and designing divisions). The main *specific knowledge task of foundries* is, based upon the cooperatively constructed common technological ground and the universal adoption of the same dedicated pieces of equipment provided by global specialised suppliers, to develop the proprietary recipes needed to efficiently use the equipment and to produce new generations of chips.

Concurrently, *the knowledge task of designers* is to adapt design methods to the new generations of chips and especially to find new applications, in order to exploit the opportunities opened by higher levels of integration and miniaturization. The growth of the semiconductor markets depends on the concurrent solution of the problems faced by manufacturers and designers. An unbalance in the capability to push forward the frontier of knowledge, on whichever side, curbs industry growth. For both categories of agents, foundries and designers, the main source of appropriability (i.e. of profitability) derives from *being first, or in the group of the first, to accomplish the specific knowledge task*, thus gaining a first mover advantage.

With regard to the technological domain, and thus to foundries (on which the attention is focused in this section), the winners of the race - who come up through trial and error with effective process recipes before competitors - are awarded an extra-profit on the knowledge gap achieved, which permits lower costs and higher yields.

However, even in this race directed to accumulate proprietary knowledge competitively, in the main field of CMOS technology at the level of complexity and standardization reached during the nineties, firms started to exhibit cooperative attitudes, in the form of know-how trading¹³. Since know-how regards a very high number of production steps, no single step is vital to the firm. Moreover, firms know that all process steps can be independently developed by any competent player, given an appropriate expenditure of time and money. When proprietary know-how has these attributes, as Von Hippel explained (1987), know-how trading is likely. In fact the benefit that overall these exchanges deliver to a firm, the reduction of the cost of independent know-how accumulation, outweighs the risk of making some gift with no recompense¹⁴.

Interestingly, know-how trading is not practiced in the fields of niche technologies, where some firm commands a profitable monopoly position, which it does not want to give up. These niches are the province of full secrecy.

¹³ Appleyard, Hatch and Mowery (2000, p.203-4) note the “surprisingly cooperative” attitude of firms, which gather data from each other on the management of new process introduction. They also note that an important source of information for integrated device manufacturers (IDM) that partly outsource to foundries the manufacturing of some internally designed chips was the interaction with these foundries. Appleyard (1996) presents interesting evidence on interfirm knowledge sharing (both along private and public channels) drawn from a survey on knowledge transfers in the semiconductor and steel industries. Unfortunately, no distinction is made between process knowledge and product design knowledge, which in the semiconductor field highly matters. According to her, an important factor which (inversely) determines the intensity of knowledge sharing (which varies across industries) is the pace of innovation. The results of the survey, however, do not convincingly validate the hypothesized inverse relationship between the pace innovation and know-how trading. In our view, the explanatory factors may vary among industries and inside industries among locations (think to districts). In the case of semiconductors, we conjecture that the main driver of know-how trading is the perception by firms of a common challenge (the complexity of the game against nature) that exceeds individual capabilities.

¹⁴ Moreover, what is exchanged is information and the recipient may not be able to understand and apply it correctly, also because pieces of equipment of the same kind but manufactured by different suppliers may have some subtle differences which impede the application of exactly the same recipe. Therefore the value of the gift may be uncertain, as well as that of the recompense.

However, the spread of reciprocated gifts may not suffice to keep affordable the cost of independent know-how accumulation. In fact, in the fabs (facilities) that firms are currently planning to build, process technologies dedicated to very large scale integration (VLSI) of transistors with feature sizes of 90 nanometres on silicon chips of 300 mm reach such a level of complexity and cost¹⁵ that few firms seem in the condition to continue to participate to the race. At least alone. In order to save scarce resources, they are induced to share *tout court* the cost of process development - namely the cost of coming up with effective production recipes –giving rise to formal coalitions to meet this target.

In fact, even though the cost of a new mass production plant (reaching about 2 billion dollars) exceeds development cost, it is not the cost of plants that manufacturers need to share, since all major players have to run more than one plant in order to serve their market (the minimum optimal plant size is much lower than market size and also of the market share of major players). Duplication of plant costs is inevitable. In contrast, what represents a waste of resources, that can be avoided by joining forces, is the duplication of knowledge creation efforts conducted by different firms with the aim of arriving to *the same result* (that of using efficiently the same, or very similar, pieces of equipment). The task of defining recipes (know-how) entails the collective effort of hundreds of experts working on pilot plants manufacturing about 10.000 silicon wafers a month¹⁶. Thus it is the cost of the pilot plant and of the research effort undertaken using it – the upfront cost of know-how creation - that can be shared. Moreover, joining forces may also bring the advantage of speeding up problem solving activity. Once the recipes are defined and codified, they can be transferred and reused at low cost to mass production plants¹⁷.

Notice that process development is a knowledge creation task fully indivisible. Experts must continuously interact among them, share the results of experimentation and tacit knowledge. The pilot plant is the object of experimentation that to a large extent dictates the boundaries of the knowledge endeavour, namely the number and extent of human interactions that must be devoted to the knowledge effort.

The coalition recently formed by StMicroelectronics, Philips and Motorola, with the participation of Taiwan Semiconductor Manufacturing (TSMC), which is explicitly intended to share the cost of technological development activity and accelerate it through joint efforts,

¹⁵ According to experts, any new technological generation, which involves a given shrinkage of feature sizes (e.g., from 130 to 90 nanometer), augments complexity by four times.

¹⁶ Mass production plants cost about two times pilot plants (2 billion dollar versus 1) and produce about 4 times (40.000 wafers a month). These modern large pilot plants are run according to the rules of industrial organization, working on 3 shifts on 7 days a week, with full traceability of the production flow (which is fundamental to understand problems under way, such as un-proper setting of a piece of equipment) etc. They guarantee a short cycle time of about one and half month. In the past pilot plants were part of laboratories and used to produce about 50 wafers a month with a cycle time of circa 9 months. Without entering into technological details, suffice it to say that with the current level of technological complexity (over 400 more or less complex steps must be performed to manufacture a chip) this development mode has become obsolete and process development has become the province of manufacturers, since modern pilot plant cannot be afforded by universities (G.E. Moore, 1996). Hence universities and public labs in the field of VLSI have focused research on particular types of equipment and problem and often perform it at the plant of a cooperating firm, where they may locate their own instrumentation. Another important aspect is that the new system of development in industrial pilot plants reduces time to market, since firms start to sell during the development phase, when they still have a low yield. Moreover, it spares the time that used to be spent in the transfer of recipes from the lab to production plants.

¹⁷ In mass production plants recipes are further improved over time through learning by using (Balconi 2002).

is a clear example of the new type of arrangement devised to face the cost of managing complexity.

The last aspect to consider is the impersonal form of exchange of technological knowledge which takes place through the exchange of patents, of even of portfolios of patents. This phenomenon has received wide attention by the literature (see in particular Grindley and Teece, 1997, and Hall and Ham, 1999).

The main point is that in cumulative technology fields such as semiconductors, one innovation builds on another and overlapping developments are inevitable. Firms need to cross-licence portfolios of all current and future patents in a field-of-use, to ensure that they have freedom to manufacture without infringement. Especially companies that operate state-of-the-art manufacturing facilities appear to face a great need to bargain with other holders of patent rights. Since this exchange permits firms to concentrate R&D in those areas in which they are most competent, they can develop complementary rather than duplicative technology, with great benefit to the efficiency of the system¹⁸. This exchange is not hindered by profitability considerations, because competitive advantage is largely driven by lead time, design competences and (for manufacturers) superior manufacturing capabilities. Due to the short product life cycles, patents are a relatively ineffective means to profit from inventions.

3. The role of university and industry in the production and dissemination of different types of knowledge in the field of circuit design

In this section we shift the attention from manufacturing technologies to the design of microelectronic circuits. We make this choice (and we omit areas of basic research such as the physics of materials underlying VLSI, microsystems, sensors, biochips, etc.) because very little is known about "the research machinery" in the field of system design, notwithstanding its importance both in the academy, in public labs and in industry. In particular, we shall attempt to illustrate the pattern of knowledge production and the division of roles between university and industry, with the aim of accounting for the high "distributional capabilities" of the system (i.e. the capability to distribute new findings through publication), based upon the high propensity of microelectronic firms to publish their research results (see the evidence presented in the next section).

Research carried on in this field is application-oriented. The objective pursued is the exploitation of the potentialities of new technologies (when they first appear, they are *obscure* with regard to their use) or the demonstration that new unexpected applications can be realized also by resorting to known technologies and creatively recombining existing concepts. However, at the most sophisticated level, the methods required to reach the outcomes are typically scientific in character, as they involve basic understanding and theory building. Actually, the *creative engineers* who perform this kind of research have to come up with innovative methodologies, new theories and mathematical formalizations of problems concerning electrical circuits. They also have to develop a full analytical understanding of the fundamental limits of circuits, in order to avoid wasting time in attempting to overcome them. The final released output of this research is constituted by prototypes, publications and patents.

¹⁸ Grindley and Teece cite (p.14) IBM which publicly stated : "there is less time to invent everything we need... IBM needs to have access to the inventions of others... You get value from patent in two ways: through fees, and through licensing negotiations that give IBM access to other patents. Access is far more valuable to IBM than the fees it receives from its 9.000 active patents. There is no direct calculation of this value, but it is many times larger than the fee income, perhaps an order of magnitude larger."

More precisely, the shrinkage (e.g. from 0.13 to 0.09 micron) of size of the elementary devices (transistors) opens the opportunity for new functions and applications, while at the same time making no longer possible to realize some types of circuits which were enabled by more mature technologies. For example, the new smaller chips are faster, but can stand lower voltages, etc. The limits of new technologies must be learned and tested. Thus the role of designers entails on one side finding out which new interesting applications are possible and whether the demands for new functions by system manufacturers can be met and, on the other side, informing the developers of technologies about the problems found, so that they can improve and to some extent correct them. Analog designers must create the interface between the real world (made of the useful and pleasant things demanded by users), which is analog, and the digital world of processors, while digital designers must build more powerful processors, integrating on a chip up to million of transistors. This implies a level of complexity which can be mastered only through the use of specialized software. In the race, new unbalances are continuously created and overcome¹⁹.

New technologies offer the potential for the introduction of different degrees of novelty, which highly differ in terms of intellectual and commercial risk. The lower degree involves replicating old products in enhanced versions, targeting markets already in existence and well known (i.e., microprocessors or memories for PCs). Coming up with these enhanced product designs is the aim of short run research, which is conducted by firms within the strict time constraints set by specific market requirements. They need to innovate in the course of the race.

Medium run research, instead, involves creating either products with new functionalities, or new applications in fields which have already started being exploited (such as certain types of wireless applications), or radically enhanced versions of existing products, which are however predictable (and usually predicted by the Roadmap) both in technological and commercial terms. For example, hard disk drive internal data rate currently reaches 850 MSps (Mega Samples per second) but research is on the way to extend this data rate beyond 2 GSps. Medium run research is conducted usually by firm research groups expressly isolated by the pressures of current needs. Increasingly, they are located in university campuses.

Long run research addresses radically new problems and products, for which markets are unexplored and unpredictable. Currently this type of research is mostly the province of universities and public research laboratories, with which the most advanced industry groups are typically networked. Under this heading it may also be located research aiming at demonstrating that old technologies may be used to do things that were thought impossible. Researchers who succeed in this kind of endeavour may decide to go on working to come up with a marketable solution, founding their own start up. Thus intellectual boldness may also give rise to entrepreneurial ventures (venture capital permitting it)²⁰.

The main aspect which differentiates academic research from industrial one is the level of risk born, involved by the complexity and especially the distance of explorations from

¹⁹ Over time, there has been an increasing use of digital techniques in place of traditional analog methods and many applications have replaced analog circuitry with their digital counterparts, such as digital audio. However, the need for analog circuit design remains strong, as they are the interface with the real world (for example, when digitising physical signals, analog-to-digital and digital-to-analog converters are always needed). In addition, new applications continue to appear, such as wireless communications, that demand the use of analog front ends due to speed and power consumption requirements. Often this analog circuitry, although it constitutes only a small portion of the total chip area, may be the limiting factor on overall system performance and the most difficult part of the IC design, as analog design is still mainly hand drafted (see Johns and Martin, 1997).

²⁰ Obviously, researchers involved in any kind of research may attempt to become rich by founding a start-up. What we want to make clear here is that even long run research *ex post* may not be far from commercial results.

existing markets. Put differently, the main diversity is the space offered to creative freedom. Naturally, a task specific of industry (either start-ups or established firms) is that of transforming original prototypes into final products (through industrialization and customisation). At this stage, knowledge is transformed from general to specific (adapted to clients' needs), through a specialised problem solving effort and know-how.

All research groups engaged in carrying on the various kinds of research (from short to long run) draw upon the stock of fundamental knowledge and sectoral culture (acquired through academic education). Moreover, researchers creating knowledge of a given time horizon not only release it "to the world" through publications, but they may also transfer it to the immediately lower level, to which usually they have direct links, since effective transfer not only implies information release but also face-to-face transmission of tacit knowledge. The interconnection between university and industry usually concerns the exchange and joint production of long and medium run knowledge. The system gets "corrupted" when firms fund university researchers to directly contribute to the production of short run knowledge. This generates tensions and lowers future opportunities. To maintain a good balance public funding is required. The higher the reputation of a university and hence the higher its attractiveness to numerous firms, the less is the danger for it to be compelled for lack of funds to surrender to myopic pressures intended to shorten the research horizon.

Relations between university and industry are very important. As synthesized in figure 1, the exchange to which relationships give rise is quite rich. Firstly, given the application-oriented character of their research endeavour, university researchers look at industry for "direction" in general, and more specifically for problems to be solved (such as the so called "brick walls", pointed out by the Roadmaps, which hinder technological development in certain more or less specific fields). From cooperating firms they also get, besides funds, important tools (such as "libraries" of circuit blocks, IPs²¹, design kits and CAD tools) which are required to speed up research and permit to concentrate efforts on the real novelties. Finally and importantly, firms cooperation is required to access production technologies, in order to get prototype chips manufactured. The latter in fact must be physically tested, since the measures revealing their effective functioning are necessary to validate the models underpinning them and to indicate whether modifications and improvements are called forth²².

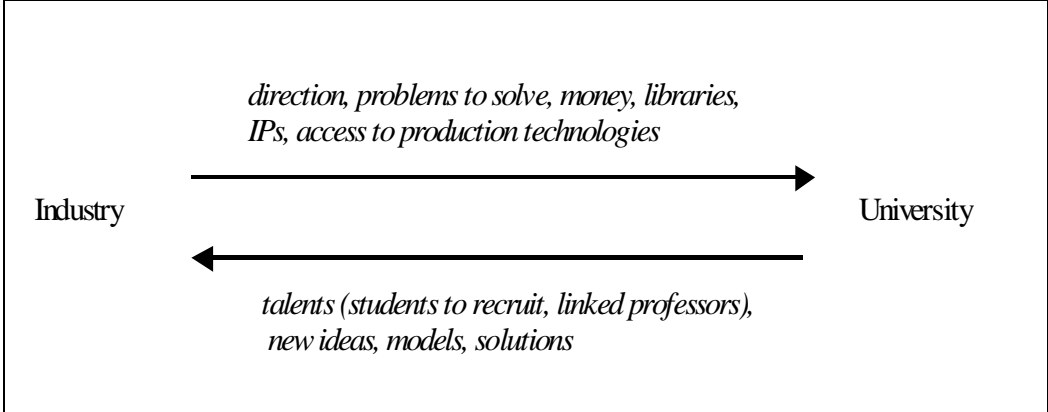
As to firms, the first interest in universities is to get enough highly-qualified engineers. The best way to recruit them (and to conduct research at low cost) is by directly testing their abilities in the accomplishment of joint research. Ideas, solutions to problems, models delivered by university professors are also very important and the establishment of direct

²¹ In the industry by IP is meant a block with a predesigned function to be implemented in a semiconductor device. An IP is not an intellectual property in the legal sense.

²² The last phase of design, which consists in producing the lay-out (as explained in note 12), must be accomplished by applying firm proprietary design rules, which slightly differ among manufacturers. University researchers, however, may access technologies (as well as design rules, libraries, design kits etc.) not only through direct links with particular collaborating firms. In fact, since the 1980s, various projects are born (such as Mosis in the United States, Europractice in the European Union, or CMP in France) with the aim of providing university, public agency and small firm designers with a single interface to the technologies of the semiconductor industry. The cost of fabricating prototype quantities is kept (relatively) low by aggregating multiple designs onto one mask set. This allows customers to share overhead costs associated with mask making and wafer fabrication. Over time the cost of a production run has increased (reaching about 500.000 dollars) and getting the prototypes manufactured represents the main cost of research.

personal links allows firms to tap professors' know-how. Ultimately, joint research with universities allows companies to leverage matching research funds from government²³.

Figure 1 - The exchange between university and industry in the field of circuit design



The previous distinction among the different kinds of research and of knowledge generated in terms of time horizon and degree of generality permits us to account for the choices firms make on whether to appropriate or disclose their knowledge (at least in the field of microelectronic design).

Our point is that the quest for profits drives firms to manage knowledge in ways that differ according to the nature of the knowledge itself. Whereas the management of the results of short run research and of problem solving activity carried on to engineer and customise prototypes and designs *is founded on appropriation*, since the products that embed those results are immediately commercializable²⁴, medium and long term knowledge, which is still too general and far from being at the core of a marketable product, *is strategically managed* with the aim of strengthening the firm's competitiveness. And in order to build competitive advantages, disclosure may be more useful than appropriation, for a number of reasons.

The main effects of disclosure through publication of papers in scientific journal are reputation and visibility, which tend to fall upon both the individual authors and the institution to which the authors are affiliated.

Considering firstly individual researchers, they are aware of the value of their human capital and of the importance of enhancing and leveraging it for their career. Usually, they are

²³ Hicks *et alii* (1996) group into two main headings the reasons why firms establish links and collaborations with other entities, in particular universities: 1) accomplishment of research efficiencies (firms cannot do everything themselves: they need to reduce costs and risks sharing them with partners and seek cross fertilisation and synergy); 2) access to technical opportunities (through the recruitment of high quality researchers, acquisition of skills in a new area, access to new knowledge and technologies, entry in a network of relations). All the listed reasons contribute to spur collaborations in the microelectronic field, however it seems that the first group is more important than the second one for process technologies, while the opposite holds for circuit designs.

²⁴ By product we do not only mean tangible product (such as chips in our case) but also patents.

not committed²⁵ to a particular employer and consider their personal success to a great extent separate from their employer's one. They tend to enrich their curriculum through multiple experiences (also entering university or public labs) and hence they are very interested in the visibility and reputation delivered by publishing. Their individual reputation for contributions acknowledged within their reference groups is thus an important "currency" in their career (albeit not the fundamental one, as in the case of academics)²⁶. No less important, creative engineers, like scientists, have a "taste" (Stern 1999) for their speculative work, and the satisfaction derived from circulating its result and finding recognition of its value from the social community of reference is a crucial motivating force. In conclusion, to the industrial researcher the disclosure of knowledge by publications, which make her talent visible, is both more advantageous (in terms of career) and more rewarding (in terms of satisfaction) than secrecy and retention ²⁷. As Stephan puts it (1996, p.1290) "Scientists and engineers often see the ability to publish as a condition of employment in industry, knowing that if they are not permitted to do so their career path will be severely restricted and they may fail to achieve prestige among their peers."

This leads us to consider the benefits that reputation and visibility acquired through publications in scientific journals deliver to firms. Consistently with what seen above, publishing permits companies to attract, recruit and retain qualified researchers. Besides this, reputation serves to attract capital and customers (this is particularly important for small firms), to link to the community of academic researchers (Nelson 1990, Godin 1996) and to access a network of knowledge exchange²⁸. Finally, published papers may forestall a competitor from patenting, limiting the area of knowledge they may appropriate (Cohen, Nelson, Walsh 2002).

Clearly these benefits contribute to competitive advantage and thus enhance firm profitability and growth. On the whole, the quest for profit drives firms to appropriate the knowledge directly embedded in marketable products (be they tangible or intangible ones), while it leaves room for discretionary rules and norms of behaviour with regard to the management of knowledge which is still far from being marketable. While adding to the stock of public knowledge is not the mission of companies, (while is the mission of the Republic of Science, as clearly stated by Dasgupta and David, 1994), contributing to the addition may be a strategic lever for the members of the Realm of Technology. Manoeuvring this lever is necessary for firms to survive and thrive in a complex world, where networking is indispensable and the aspirations of mobile and unquiet talents must be to a certain extent accommodated.

²⁵ Note that if the employer is a big firms, no commitment can be warranted by stock options, since no connection exists between one's own efforts and the stock market's valuations of the firm's share (Bebchuk, Fried, Walker, 2002).

²⁶ Add to this "personal interest story" the fact that now many firms consider the number of publications, in addition to the number of patents, as an indicator of researchers' productivity, which they can monitor (in contrast to effort). In this way they push to publish. But why this is so, may be better understood after the discussion of firms' quest for reputation.

²⁷ Overall, the willingness to circulate one's own original contributions and gain recognition seems to be inherent to the search for fame and not only to be elicited from the particular reward structure that governs the community of academic scientists. However, it is only the reward system of the Republic of Science which is fully compatible with the ambitions and motives of intellectual fame-seekers, because of its fundamental institutional goal (adding to the stock of public knowledge).

²⁸ According to Hicks (1995, p.422) "publications signal the existence of tacit knowledge and other unpublishable resources, thus building the credibility needed to find partners in knowledge exchange".

Moreover, in the field of microelectronics the company which publishes retains a crucial time advantage with respect to the readers, not only because publications disclose knowledge with a certain delay, but also since the written text does not reveal completely (often purposefully) what should be known in order to replicate a circuit or an architecture. Due to this characteristic, publishing involves very little risk of being counterproductive, by disclosing useful knowledge to competitors²⁹.

Finally, the problem must be considered that some of the above mentioned advantages can be delivered to a certain extent also by patents, especially given the "defensive" nature of patents which is typical of this sector (as explained in the previous section). In general, publications and patents are reconciled and not mutually exclusive, even though in order to patent firms tend to defer publication. However, it does not seem that patenting has been slowing down scientific communication in a significant way.

On the whole, academicians are more free to pursue their own research interests than industrial researchers, and it is not clear whether they do really pay something in exchange (accepting a lower salary than the latter). In fact they can add to their university salary income earned as consultants and pecuniary gifts from industry. Moreover, in the United States, where mobility between university and industry is high, universities pay a higher salary to microelectronic professors than to those specialised in fields unaffected by external labour market competition. However, even a good academic salary looks very low when compared to the earnings of successful entrepreneurs.

Especially in the environment of the end of the 1990s, in the middle of the bubble, the prospect of high profits became an opportunity cost no longer acceptable for many professors. Thus a number of academic researchers, enticed by the prospect of profits, began to found their own start up. Given the availability of foundries and the abundance of seed and venture capital, the entrepreneurial venture could be perceived as an easy game to play and probably the entrepreneurial risk was to a large extent undervalued.

The start-up is often based on an invention that was patented, and is the tool for carrying on the work of industrialization (development of specific knowledge), which often is executed by ex-students, involved in the original research and recruited by the new firm. The professor-founder may either leave the academy to become full time entrepreneur, or retain her academic position and participate to the board³⁰.

Universities had to resign to the drain of talents, making the best of an unfortunate situation, in their own right. They began to boast of their spin-off record, in order to continue to attract resources. But for the Republic of Science the shift of talents to the job of industrialization, in the quest for appropriation of the results of long term research, could

²⁹ This possibility of retaining a competitive advantage over competitors while gaining recognition through publishing was recognized by Eisenber (1987) with reference to the field of biotechnology.

³⁰ Many start-ups originated as well from research undertaken in public labs. MIT Lincoln Laboratory is an interesting case. The Lab functions as one of the about 10 Federal Contract Research Centers (FDRC) for the U.S. government and is funded mainly by the Department of Defense (DOD) and the FAA (Federal Aviation Administration). It specializes in carrying out component, circuit, and systems development efforts deemed too risky, or inappropriate, by commercial organizations. Once there is a large effort in industry on a particular topic, the lab migrates to other research topics. The main factors of attraction of researchers are the opportunity to do front end research, to get easy funding from the Air Force and the freedom from teaching requirements. Basically, since it is the industry which pays the highest rewards, Lincoln Lab researchers are mainly technology driven, and especially motivated to do research in those particular areas where the Labs are focused. However, 80 high-technology companies have evolved from the Laboratory's technology development, in fields which range from multimedia software services to advanced semiconductor lithography.

more and more represent a real problem. It might well be that the current economic crisis, unveiling the real meaning of entrepreneurial risk, will lead to a new balance, discouraging over-hasty entrepreneurial ventures by academics and drying-up the flow of exit of talents from Science into Technology.

4. Some evidence on increasing cooperation in research

In this section we examine the contribution delivered by industry to the dissemination of knowledge through publications in scientific journals and we compare it with the performance of other institutions. We also want to see whether the increasing cooperation among various entities in conducting research is mirrored in the growth in the number of publications whose co-authors are affiliated to different institutions, compared to those signed by researchers belonging to the same entity.

Thus we have scanned some of the most important IEEE journals (*Transactions on Electron Devices*, *Electron Devices Letters* and *Solid State Circuits*) and confronted the distribution of papers by type of author in the year 1989 with that of the year 2000. In particular we have subdivided papers by the following criteria: i) according to the type of institution to which the authors are affiliated (universities, companies, public labs and other entities of minor importance, such as private labs); ii) according to whether their co-authors are affiliated to the same institution or belong to more than one.

Table 1 shows that in the year 1989 the main contributor to the stock of public knowledge were companies, which generated 45,5% of the papers authored by a single entity (*versus* 30,2% by universities). Collaborations represented only 21,2% of papers published. Overall, companies authored 60,3% of the total amount of papers and universities 47,9%. During the period examined two dramatic changes took place.

Firstly, the propensity of firms to publish alone collapsed (from 45,5% to 20,3%), and it was not fully compensated by the higher propensity to publish articles coauthored with other institutions. Consequently, on the whole, universities acquired the primacy in terms of publications. This is consistent with the shift of firms' focus to short run research, and with their increasing cooperation with universities in the conduct of the more risky research projects. Indeed the situation in 1989, when the primacy belonged to firms, was exceptional and was probably a legacy of the role traditionally played in the sector by Bell Labs, IBM labs, Fairchild Semiconductor etc.

Secondly, as expected, the share of articles produced by cooperative cross-institution research efforts strikingly increased, from 21,2% of the total in 1989 to 45,6% in the year 2000³¹. Notably, the trend is very similar for each journal³².

Tab.1 - Distribution of articles published by the journals *Transactions on Electron Devices*,

³¹ The increase of cross-institution collaborations in the field of microelectronics corresponds to a more general trend, which is partly due to the reduction of the geographical and cost barriers enabled by the advances in IT. See National Science Foundation (NSF), *Science and Engineering Indicators 2002, Chapter 5, and Appendix*, table 5-45, on multiple corporate authorship of U.S. scientific and technical articles.

³² While *Transactions on Electron Devices* and *Electron Devices Letters* focus on the physics of the semiconductor devices *Solid State Circuits* is the most important journal in the field of circuitry design. The full documentation and analysis of each journal is available by the authors. As to more general trends regarding the U.S. scientific and technical literature, from 1988 to 1999 the percentage of articles authored by industrial researchers remained stable (around 11%), since the remarkable decrease in physics (from 21% to 14%), engineering and technology (from 18% to 16%), chemistry (from 14% to 11%) and other fields was compensated in particular by the rapid increase in clinical medicine (from 19% to 31%) and, to a lesser extent, in biomedical research (from 11% to 14%). See NSF, *ibidem*. On the increase in industry publication in the 1980s, as evidenced by the record of 34 large European and Japanese companies, see Hicks *et alii*, 1996.

Electron Devices Letters and Solid State Circuits by type of author

<i>Type of contributor</i>	<i>1989</i>		<i>2000</i>	
	<i>N.of articles</i>	<i>%</i>	<i>N.of articles</i>	<i>%</i>
Single university	258	30,2	252	32,6
Single company	388	45,5	157	20,3
Single public laboratory	19	2,2	9	1,2
Other single entities (priv labs)	7	0,8	2	0,3
<i>Total single entities</i>	<i>672</i>	<i>78,8</i>	<i>420</i>	<i>54,4</i>
Collaborations inter-uni	35	4,1	85	11,0
Collaborations inter-companies	17	2,0	27	3,5
Collaborations uni-companies	96	11,3	185	24,0
Other collaborations	33	3,9	55	7,1
of which: coll others-companies	13	1,5	31	4,0
<i>Total collaborations</i>	<i>181</i>	<i>21,2</i>	<i>352</i>	<i>45,6</i>
<i>Total</i>	<i>853</i>	<i>100,0</i>	<i>772</i>	<i>100,0</i>
Of which: Company tot.(single and coll.)	514	60,3	400	51,8
University tot.(single and coll.)	409	47,9	546	70,7

All types of collaborations have grown (cross-university, cross-company, with public or private labs), but the growth of collaborations between university and industry is especially remarkable. Moreover, it is the behaviour of firms which most drastically changed over the period.

Another interesting aspect which is illuminated by the analysis of publications³³ is the substantial increase in the number of entities producing them (table 2).

Tab.2 - Number of entities contributing to papers published in EDL, TED, SST

	1989	2000	2000/1989
Universities	235	368	+57%
Public labs	38	49	+29%
Companies & priv.labs	201	220	+9%
<i>Total</i>	<i>474</i>	<i>637</i>	<i>+34%</i>

It can be observed (table 3) that at the worldwide level the United States are the only area expressing a diminishing number of contributing entities (from 262 to 247), while the contributors from Asia augmented drastically (from 71 to 180, +254%) and the European ones to a considerable extent as well (from 133 to 186, +40%). In both areas, universities are the institutions more intensely committed to catching up. In the year 2000 one finds a higher number of Asian and European universities publishing in the 3 IEEE journals than North American ones. However, North American universities are more productive, realizing a higher number of contributions. University of California and Stanford University are on top and leave behind at a remarkable distance all their competitors, but it is extremely interesting

³³ The total number of papers published by the 3 journals, as figure 1 shows, decreased by about 10% in the decade. This does not mean that overall in the field of microelectronics the total amount of publications diminished. In fact, in the period there has been an increase in the number of books and proceedings published, and some new journals have been launched. However, according to some knowledgeable insider, the complexity of designs has increased to such an extent, that it takes longer to produce serious papers than in the past, since a design project may take years of risky commitment, and one has to wait for the result in order to publish something "of weight". Thus, unfortunately, it seems that especially due to collusive behaviour among academics the standard of selection has lowered and a higher number than in the past of publications of rather low level tends to be published.

that universities such as National Taiwan University, Seoul National University or the Swiss Federal Institute of Technology now rank high in the world scenery (table 5). Overall, the North American leadership in the production of open knowledge in microelectronics is retained, but in the nineties the distance with other areas has decreased to a very large extent (the contributions of North America having diminished from 59% to 43% of the total)³⁴.

Tab.3 Number of contributions to papers published in EDL, TED and SST according to the geographical origin of the contributing entities

	Companies		Universities		Public Labs		Total	
<i>Number of contributing entities 1989</i>								
North America	126	63%	114	49%	22	58%	262	55%
Asia	33	16%	33	14%	5	13%	71	15%
Europe	41	20%	81	34%	11	29%	133	28%
Others	1	0%	7	3%	0	0%	8	2%
Total	201	100%	235	100%	38	100%	474	100%
<i>Number of contributing entities 2000</i>								
North America	122	55%	106	29%	19	39%	247	39%
Asia	55	25%	114	31%	11	22%	180	28%
Europe	39	18%	133	36%	14	29%	186	29%
Others	4	2%	15	4%	5	10%	24	4%
Total	220	100%	368	100%	49	100%	637	100%
<i>Number of contributions to papers 1989</i>								
North America	303	54%	302	64%	33	61%	638	59%
Asia	164	29%	49	10%	8	15%	221	20%
Europe	88	16%	111	24%	13	24%	212	20%
Others	1	0%	7	1%	0	0%	8	1%
Total	556	100%	469	100%	54	100%	1079	100%
<i>Number of contributions to papers 2000</i>								
North America	253	53%	267	37%	35	42%	555	43%
Asia	148	31%	225	31%	24	29%	397	31%
Europe	76	16%	219	30%	19	23%	314	24%
Others	4	1%	18	2%	5	6%	27	2%
Total	481	100%	729	100%	83	100%	1293	100%

Note: Since we want to measure the presence of the various areas in the system of knowledge production disaggregated into its various institutional components, we count the number of contributions of each area (namely the number of times a given area appears in the addresses of the institutions to which the authors of papers are affiliated). The sum all areas' contributions is obviously higher than the number of papers, due to co-authorships both cross-area and cross-institution. For a discussion on the way to calculate the contributions of the various participants to the production of papers see Godin and Gingras (2000).

Moreover, the importance of “Not-North-Americans” in contributing to the worldwide flow of open knowledge results further augmented, if one considers the geographic origin of the authors affiliated to US entities. We have conducted this analysis only for the journal SSC, comparing the situation in 1989 with that in the three years 1999-2001. As shown in table 4, no significant change has emerged in the period, during which about 30% of the authors affiliated to US entities are foreigners, especially from China, Taiwan, Korea and even Iran.

³⁴ In the same period the total number of scientific publications by North America declined from 42% (1989) of the world total to 35% (1999), while Asia augmented its share from 11% to 16% and Western Europe from 31% to 36% (NSF, *ibidem*).

Tab.4 Geographical origin of authors affiliated to US entities who published papers in SSC

	<i>(yearly average 1999-2001)</i>		<i>1989</i>	
USA	705	65,6%	219	68,2%
China	48	4,5%	1	0,3%
Taiwan	40	3,7%	25	7,8%
Korea	37	3,4%	7	2,2%
Iran	35	3,3%	0	0,0%
U.K.	19	1,8%	4	1,2%
Germany	19	1,8%	3	0,9%
Japan	17	1,6%	5	1,6%
Canada	16	1,5%	5	1,6%
Switzerland	12	1,1%	0	0,0%
Other nationalities (1)	84	7,8%	45	14,0%
Total foreigners (2)	327	30,4%	95	29,6%
Nationality unknown	43	4,0%	7	2,2%
<i>Total authors of articles by US entities</i>	<i>1075</i>	<i>100,0%</i>	<i>321</i>	<i>100,0%</i>

(1) In 1989 11 authors were from India and 7 from Australia.

(2) 84% of whom (275) got a post graduate degree in the US in the period 1999-2001, and 71% (67) in 1989.

Tab.5- The most important contributors to SSC (1999-2001)

<i>Companies</i>	<i>N.papers</i>
Philips (Netherlands)	31
IBM (USA)	29
Toshiba (Japan)	23
Siemens (Germany)	22
Agere (USA)	21
Mitsubishi (Japan)	21
NEC (Japan)	21
Intel (USA)	19
NTT, (Japan)	18
Hitachi (Japan)	17
Samsung Electronic (Korea)	14
Motorola (USA)	13
Texas Instruments (USA)	13
STM (France, Italy)	12
Broadcom (USA)	11
<i>Universities</i>	<i>N.papers</i>
University of California (USA)	67
Stanford University (USA)	34
National Taiwan University (Taiwan)	18
Swiss Federal Inst.of Technology (Switzerland)	17
Seoul National University (Korea)	13
M.I.T.,Cambridge (USA)	12
National Chiao-Tung University (Taiwan)	11
University of Pavia (Italy)	11
Katholieke Uni Leuven (Belgium)	10
Korea Advanced Inst.of Technology (Korea)	10

We added to the picture the consideration of the other important flow of open knowledge constituted by papers presented to conferences. We limited our examination to the 2002 IEEE International Solid-State Circuit Conference, which is considered the most important one with regard to circuit design. Here we find that papers contributed by companies amount to 71% of the total. This can be explained by the nature of the papers, which are less analytical than those published in the journals examined above and more focused on showing why a certain application brings forward the-state-of-the-art. It seems that the distribution of papers among the various types of institution that we find at this conference corresponds to a typical pattern which goes back in the past.

As is well known, during conferences a rich informal knowledge exchange among the participants also takes place. Since in the most important conferences a severe selection of papers is carried out, the authors of those accepted get a reputation which is important for their career. Moreover, these meetings are important occasions for recruiting and establishing new links among the members of the epistemic community.

Tab.6 - Distribution of papers presented at the 2002 IEEE International Solid-State Circuit Conference by contributing entity and by geographical area

	<i>N. of papers</i>	<i>%</i>
<i>Total number of papers</i>	189	100%
<i>of which: by single entities</i>	140	74%
<i>by collaborations</i>	49	26%
<i>Papers contributed by companies</i>	153	71%
<i>Papers contributed by universities</i>	61	29%
<i>Total (with duplications*)</i>	214	100%
<i>Nationality of authoring entities</i>	<i>N. papers</i>	<i>%</i>
North America	146	52%
Europe	65	23%
Asia	65	23%
MiddleEast	4	1%
Australia	1	0%
<i>Total (with duplications*)</i>	281	100%

Note: * Papers coauthored by companies and universities are counted twice, and papers coauthored by entities of different countries are counted more than one time.

5. The division of innovative labour in design and the market for design information

The last aspect to consider is how the social organization of design labour evolved in response to the complexities and uncertainties generated by the increasing miniaturization, which augmented the opportunities for new applications and pushed to the integration into a single chip of a growing number of functionalities. Large established firms had difficulty to meet these challenges, leveraging internal resources only. This paved the way to the entry and development of new design firms, which was possible because: i) manufacturing technology had been standardised, and proprietary design rules were largely similar (as was explained in section 2); ii) ICTs were able to support complex, arm's-length collaborations between designers and distant manufacturers; iii) equipment and software tools were available (in

particular workstations and simulators) that permitted designers to run experiments without silicon³⁵.

Firstly, large established companies are not the place most suitable to the exploitation of new ideas. As Gordon Moore phrases it (1996, p.171): "Even an idea recognised to have the potential to be important in a few years is not likely to be accorded sufficient attention and assigned the best people, precondition for germination. Running with the ideas that big companies can only lope along with has come to be the acknowledged role or the spin-off, or start up." In addition, ideas which might be targeted to market niches do not arouse the interest of large firms.

Thus the task of carrying out experimentation and making bets to create or to tap markets that were rapidly evolving in unpredictable ways was accomplished by start-ups in the first place. At the end of section 2 we hinted at the wave of start-ups founded by academics to carry on the design engineering work which is required to come up with marketable products. Besides universities and public laboratories, established firms have been the most important reservoirs of future start-up founders.

Since the main resource deployed to produce new applications is the labour of the most productive designers³⁶, a start-up is actually the means designers put in place in order to appropriate the value of their human capital. Thus *a decentralization of the system of production of "design knowledge"* has been driven by designers' *thrust to self-empowerment*, enticed by great profit opportunities. Very simply, they are aware that their design capability, their experience and ideas may make them very rich, if they manage to build effective teams and to raise capital and if the ideas they launch prove to intercept evolving market trends. They take a high entrepreneurial risk, but they also know that in case of failure, their human capital is still a very valuable means of knowledge production and they can go back to large firms as employees. Mobility is high, and designers' sense of belonging is towards the professional community. This is centred in Silicon Valley (and other high-tech locations in the United States) but increasingly is spreading to other countries, especially around universities of a high standing in microelectronics, from where emigration (both of graduates and undergraduates) to the Valley is still originating (due to the concentration of opportunities it offers) but towards which a reverse flow of returnees starts being directed.³⁷

The new fabless companies arrived where large firms were not able to arrive and gained market shares at their expense, since they were able to deliver more innovative designs and shorter delivery times³⁸. Their contribution to innovation may be appreciated considering the products and markets in which they operate: as to products, 43% of them concentrates in analog/mixed signals (data converters and radio frequency applications such as mixers, radios, transmitters and receivers, filters, amplifiers) and, as to markets, 54% concentrates in communications (see www.fsa.org). Thus they are focused to a large extent on the most complex (analog) and innovative fields of circuit design, which continued to grow in importance in recent years, driven by communications-related markets.

³⁵ For an account of the structural changes of the semiconductor industry see Macher, Mowery and Simcoe (2002). A more general discussion of modular production networks relying on contract manufacturing in the electronic industry is offered by Sturgeon (2001).

³⁶ Likewise, in the biotech case, the main resource around which firms are built is "the labour of the most productive scientists" (Zucker, Darby and Torero, 1997)

³⁷ See Saxenian and Hsu (2001) on the community of US-educated Taiwanese microelectronic engineers.

³⁸ The fabless segment (which started to develop in the 1980s) exceeded the growth of the overall semiconductor market by nearly double. Success can also be measured by the creation of leading fabless companies in the 3D graphics, programmable logic and communications markets, among others.

The innovation drive of fabless companies is not limited by the constraints set by production capacity, both in terms of product variety and scale. If a new design is successful in the marketplace, the innovating firm can increase its revenues at a very rapid pace, since foundries' capacity that can be tapped is wide. Market incentives are really high-powered. Seen from the other side, since foundries put their leading-edge capacity at the service of successful product innovators, capacity utilisation is not constrained, as in the case of integrated device manufacturers (IDMs), by the product innovativeness of the company itself.

In conclusion, the decoupling of applications' design from capacity management is an efficient solution not only in that it increases the scope and timeliness of innovative experimentation, but also from the angle of static efficiency and of the flexibility injected into the system.

What we are telling, however, is not at all the story of the extinction of IDMs or, more generally, of large firms. In fact, in all cases where innovative solutions are successful and purported market niches prove to be huge gold mines, IDMs become very active in the market for firm acquisitions³⁹. Thus while at the start they loose brilliant talents⁴⁰, they often end up acquiring competences (the organised teams of designers), intellectual property and market shares (albeit at a high price)⁴¹.

Now we come to the second challenge, the one set by fact that the current level of density and miniaturization enables a whole printed circuit board of 20 or more IC's to be integrated into one or two chips. System-on-chip (SoC) is the term most frequently used to describe the highly integrated devices, which have great potential to lower the total system cost, while increasing reliability and operating speeds and lowering power consumption. These advantages not only enhance the characteristics of existing electronic end-products⁴², but also open the way to new applications.

The new SoC paradigm involves that an increasing number of functional design elements must be integrated. Since no company can develop internally all of the resources and skills required (especially as SoCs becomes larger and more complex), a market for design blocks (also called design modules, virtual components or IPs) has emerged (Linden and Somaya, 2000). These blocks are not packaged components, but *design information* (supplied mostly as a lay-out description or in a hardware description language like VHDL) which is

³⁹ As put by Williamson (1975, p.205-6): "An efficient procedure by which to introduce new products is for the initial development and market testing to be performed by independent investors and small firms (perhaps new entrants) in an industry, the successful developments then to be acquired, possibly through licensing or merger, for subsequent marketing by a large multidivisional enterprise...Put differently, a division of effort between the new product innovation process on the one hand, and the management of proven resources on the other way may well be efficient".

⁴⁰ Note that in some cases the formation of firms by designers was induced by IDMs themselves, since they need to outsource part of design work, to reduce fixed costs. These "design houses", however, do not sell chips but only the labour of designers and are dependant on a single or few clients. They are provided with chip specifications by the clients and are not innovators like fabless. However, they may evolve towards the fabless model over time.

⁴¹ For example, Intel just announced it plans to invest \$150 million in companies developing high-speed wireless networking technology, an area of growth that Intel sees as key to accelerating revenue and profit in the coming years.

⁴² Systemist firms (OEMs) pushed chip providers towards SoCs. Moreover, in order to protect their system knowledge, they themselves started to build teams of microelectronic designers.

licensed and can be electronically exchanged⁴³. Monitoring of externally available design modules has become a strategic imperative even for largest firms.

Since a design module developed by a specialised firm may be sold to different clients for different uses, increasing returns may be captured over design knowledge embodied in modules and duplication of efforts can be avoided.

However, important obstacles to the development of markets for design modules remain.

Firstly, different blocks put on the same die interact in ways that are not precisely predictable by the user. Therefore they cannot simply be "copied and pasted". More advanced is the technology of the single block, the worst is the problem of integration of different blocks⁴⁴. At present, the main complexity in microelectronic design is no longer the creation of single blocks of functions, but mainly system integration on the same die of different blocks.

A single block has a standard way to be designed. Changing the technology, some models and parameters must be changed to make computations and to evaluate the block trade-off in the design, but the "concept" that is used to design remains equal. In contrast, there isn't a smart way to project systems. That's why the productivity of design methods is increasing at a rather low pace compared with the increase of the density of devices.

Every company develops its proprietary way⁴⁵ to design blocks of functions that can be sold as they are to other companies that are in delay in the development of that particular piece of knowledge. But the user needs a support to understand how to use those "cold" blocks in the most correct way.

Usually firms making SoCs create a team with the task of integrating the blocks. Each person of the team participated in the design of a single block and therefore exactly knows what can interact with its functioning and what doesn't. The leader of the SoC project has a very important management role, both technically and relationally (since the interaction among individual designers does not usually develop smoothly and without conflicts). He draws upon by the experience and knowledge acquired working on different projects, to understand technically how to manage the problems and how to choose, given the existing degrees of freedom. Being a technical leader, he can acquire the respect of the designers.

To decide which technical solution will be the best for a precise SoC requires considering all the technologies and the different solutions available and filtering them out until one single final solution is reached. Usually, the best solution for the SoC is not the best solution for the single blocks' functions. The latter have to be just good enough to let the complete system work as required by the technical specifications. In this decision various trade-offs are evaluated, regarding the cost, the time to market, the reliability and other different variables that could vary from company to company, such as the capital available to develop the project, how to use the different designer groups together, etc.

⁴³ According to Hall and Ham (1999, p.25) stronger patent rights may have supported a market for know-how exchange involving entrant firms and have facilitated specialization in the industry. However, design modules which are licenced comprise also non patented information and it seems that rapid time-to-market is the most effective lever to capture markets and to make profits also in the case of modules. On "markets for technology" in general see Arora, Fosfuri, Gambardella (2001).

⁴⁴ Brusoni and Prencipe (2001) have shown that also in the cases of aircraft engines and chemical plants "knowledge integration is not a matter of 'picking, mixing and matching' readily available knowledge modules".

⁴⁵ Designers follow the rules set in the firm proprietary design bluebook to design blocks and to prepare the related documentation. This facilitates design block reuse also in-house.

Overall, the market works for simple commodity blocks, which function also within SoCs. The most successful providers of complex modules (such as ARM), address the problem of interconnectedness with other design parts by devoting significant resources to help diagnose and solve customer problems⁴⁶. Thus the exchange of these complex modules is far from being at arm's length.

Large firms (which are the main providers of SoCs in general and the only providers of the largest and most complex ones) tend to develop strategic blocks internally, to develop in partnership with specialist providers other complex blocks and to buy on the market commodity blocks.

As clearly synthesized by Macher, Mowery and Simcoe (2002).

The presence of unexpected interactions among design blocks makes it impossible for IP vendors to give complete performance specifications for their design blocks on any but customer-by-customer, product-by-product basis, eroding many of the purported advantages of design trading. Although Internet-based exchanges now include provisions for simulating the performance of design blocks and the interactions among them, "thick" IP markets will require the creation of standard contractual and pricing practices, along with standard for benchmarking, reporting and interfacing with other design blocks...Negotiations over such standards are fraught with complexity and conflicting incentives among the parties.

Although the Internet, which is an ideal location for "virtual marketplaces" for intangible goods, will contribute to further develop the market for IPs, as is actually happening, and thus to enhance the division of design labour, the problem remains that in order to realize a SoC the user not only needs design information on the various blocks, but also the support of block designers' tacit knowledge and cooperation (except for the most simple cases).

6. Conclusions

The system of knowledge creation and distribution in the field of microelectronics has evolved in a very functional way, driven by the need to meet the challenge of complexity. The evolution has been partly managed through a coordinated effort, directed to diminish uncertainty and to further the growth of the industry, and partly unplanned and decentralised, on the initiative of professionals who became entrepreneurs to profit by the opportunities that established firms were unable or unwilling to capture.

Overall, the market potentialities opened by the increasing miniaturization of devices have far outgrown single firm's capabilities to explore them.

The role of universities as a source of knowledge has grown, since firms mostly gave up long run research. The interconnections between university and industry have been increasing, and this augments the need to defend the freedom of research objectives through public funding, in order to preserve the functionality of the system and its ability to deliver timely and open dissemination of results.

The figure below synthesizes the modes of accessing external knowledge in the microelectronic research and innovation system. Even largest firms need to absorb knowledge from outside to a great extent and to resort to all of the modes of access presented below.

Figure 2. The modes of access to knowledge created by third parties

⁴⁶ According to Linden and Somaya (2000) the ratio of support to design effort can be as high as *three to one*.

<i>Access Stage</i>	<i>Bilateral or multilateral</i>		<i>Universal (public)</i>
	<i>Personal</i>	<i>Impersonal</i>	<i>Impersonal</i>
<i>Competitive (specific)</i>	Joint know-how creation Transfer to partners Know-how trading (Informal conversations)	Patent licences IPs' trade	Patent documents* (* use restricted)
<i>Precompetitive (general)</i>	Joint research (Informal conversations)		Publications Presentations

The precompetitive stage includes the results of long run and medium run research. The competitive one comprises short run research and engineering specific knowledge. The personal mode entails transfer of tacit knowledge among members of different entities. It includes mainly face-to-face exchanges, but also exchanges mediated by telephone or e-mail, with a personal character. Impersonal transfers, by contrasts, are at arm's length. By the impersonal mode, knowledge creators do not directly contact each other and what is disseminated is knowledge codified as information, that can be electronically transferred (written text, design information). Universal access is by definition impersonal, and concerns knowledge put in the public domain. We parenthesise informal conversations, through which knowledge leaks, since here the focus is on more purposive modes of accessing knowledge.

What we want to emphasize is that the personal modes of access are much more important in the sector than the impersonal, arm's length ones, as far as specific knowledge is concerned. Patent licences are mainly passive, in the sense that they do not really serve to access new knowledge, but only to be free to use one's own knowledge. Arm's length IPs' trade is useful only to access simple pieces of design information.

Thus networks, and not markets (for design information), are the really crucial means to access external specific knowledge for semiconductor companies (obviously the market for acquisitions and the labour market are essential to acquire competences and talents).

ICTs are then very useful to connect networked individuals, among whom rich exchanges of knowledge (codified and tacit) can take place. It is also important that through the Internet virtual markets for codified design information are developed, to enable the trade of simple design blocks, but on the whole the role of markets to access new complex and specific knowledge is necessarily limited.

References

- Appleyard M.M, 1996, "How Does Knowledge Flow? Inter-Firm Patterns in the Semiconductor Industry", *Strategic Management Journal*, vol.17 (Winter Special Issue), 137-154.
- Appleyard M.M., N.W.Hatch, D.Mowery, 2000, "Managing the Development and Transfer of Process Technologies in the Semiconductor Manufacturing Industries" in G.Dosi, R.Nelson,

- S.Winter (eds.) *The Nature and Dynamics of Organizational Capabilities*, Oxford University Press, Oxford.
- Arora A., A. Fosfuri, A. Gambardella, 2001, "Markets for Technology and their implication for Corporate Strategy", *Industrial and Corporate Change*, 10, 2, 419-51.
- Balconi M., 2002 "Tacitness, codification of technological knowledge and the organization of industry", *Research Policy*, n.31, 357-379.
- Bebchuk L.A., J.M.Fried, D.I.Walker, 2002, *Managerial Power and Rent Extraction in the Design of Executive Compensation*, Discussion Paper N.366, Harvard Law School, June.
- Brusoni S. and A.Prencipe, "Unpacking the Black Box of Modularity: Technologies, Products and Organizations", *Industrial and Corporate Change*, 10, 1, 179-205.
- Cohen W.M., R.R.Nelson and J.P.Walsh, 2002, "Links and Impacts: The Influence of Public Research on Industrial R&D", *Management Science*, vol.48, n.1, 1-23.
- Dasgupta P. and P.A.David, 1994, "Towards a new economics of science", *Research Policy*, 23, 487-521.
- Eisenberg R.S., 1987, "Proprietary Rights and the Norms of Science in Biotechnology Research", *The Yale Law Journal*, 97, 2, 77-230.
- Godin B., 1996, "Research and the practice of publications in industries", *Research Policy*, 25, 587-606.
- Godin B., Y.Gingras, "The place of universities in the system of knowledge production", *Research Policy*, 29, 273-278
- Grindley P.C., Teece D.J., 1997, "Managing Intellectual Capital: Licensing and Cross-licensing in Semiconductors and Electronics", *California Management Review*, 39,2, 8-41.
- Hall B.H. and Ham R.M., 1999, *The patent paradox revisited: determinants of patenting in the US semiconductor industry, 1984-94*, NBER Working Paper 7062.
- Ham R.M., G. Linden, M.M. Appleyard, 1998, "The evolving role of Semiconductor Consortia in the United States and Japan", *California Management Review*, vol.41 (1), 137-163.
- Hicks D., 1995, "Published Papers, Tacit Competences and Corporate Management of the Public/Private Character of Knowledge", *Industrial and Corporate Change*, vol.4 (2), 401-424.
- Hicks D., P.A. Isard, B.R.Martin, 1996, "A morphology of Japanese and European corporate research networks", *Research Policy*, 25, 359-378.
- Katz M., J.Ordovery, 1990, *R&D cooperation and competition*, Brookings Papers on Economic Activity.
- Johns D., K.Martin,1997, *Analog integrated circuit design*, John Wiley & Son, New York.
- Langlois R.N. and W.E.Steinmueller, 1999, "The Evolution of Competitive Advantage in the Worldwide Semiconductor Industry", 1947-96, in D.C.Mowery and R.R.Nelson (eds.) *Sources of Industrial Leadership*, Cambridge University Press, Cambridge, 19-41.
- Linden G., D.Somaya, 2000, *System-on-a-Chip integration in the Semiconductor Industry: Industry Structure and Firm Strategies*, October 20, mimeo.
- Lucchini N., 1998, "European Technology Policy and R&D Consortia: The Case of Semiconductors", *International Journal of Technology Management*, vol.15 (6), 542-555.

- Macher J.T., Mowery D.C., D.A.Hodges, 1998, "Reversal of Fortune?" *California Management Review*, 41,1, 107-136.
- Macher J.T., D.C. Mowery, T.S. Simcoe, 2002, "e-business and disintegration of the semiconductor industry value chain", *Industry and Innovation*, Vol. 9, N.3.
- Moore G.E., 1996, "Some personal perspectives on research in the semiconductor industry", in R.S. Rosenbloom and W.J. Spencer (eds.), *Engines of innovation*, Harvard Business School Press, Boston.
- National Science Foundation, 2002, *Science and Engineering Indicators*.
- Nelson R.R., 1990, "Capitalism as an engine of progress", *Research Policy*, 19, 193-214.
- Rosenberg N., R.R.Nelson, 1994 "American universities and technical advance in industry", *Research Policy*, 23, 323-348
- Saxenian A.L., 2001, "The Silicon Valley- Hsinchu connection: Technical Communities and Industrial Upgrading", *Industrial and Corporate Change*, vol.10, n.4, 893-920.
- SIA, 2002, *SIA Position on Federal Science: Increase support of University Research*, January 8.
- Stephan P. E., 1996, "The Economics of Sciences", *Journal of Economic Literature*, vol. 34, September, 1199-1235
- Stern S., 1999, *Do scientists pay to be scientists?* NBER, WP 7410.
- Sturgeon T.J. 2001, "Modular production networks: a new American model of industrial organization", *Industrial and Corporate Change*, vol.11, n.3, 451-496.
- Von Hippel, E., 1987, "Cooperation Between Rivals: Informal Know-How Trading", *Research Policy* 16, 291-302.
- Williamson O., 1975, *Markets and Hierarchies: Antitrust analysis and Implications*, The Free Press: New York.
- Zucker L.G., M.R.Darby, M.Torero, 1997, *Labour mobility from academe to commerce*, NBER, WP 6050.