Semiconductor Industry Dynamics.
An investigation for a General Pattern of Evolution

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1. Introduction

The link between innovation and market structures has been widely described by the literature (Dasgputa and Stiglitz, 1980, Nelson and Winter, 1982, Jovanovic and Mac Donald, 1994, Klepper, 1996, Sutton, 1998). But one of the challenges emphasised by empirical analysts (e.g. Pavitt, 1984, Pavitt et al. 1987, Geroski, 1990) is to explain strong sectoral differences and non-linear relations between firm size (or concentration) and innovation intensity that limit traditional arguments such as scale effects or first mover advantage. Neo-Schumpeterian scholars (Nelson and Winter, 1982, Malerba and Orsenigo, 1993, 1996, Dosi et al. 1997, Audretsch, 1995) argue that the answer may be found in the persistence of different regimes of innovation that generate heterogeneous structural conditions for firms' conduct and performances.

Another stream of the literature argues that market structures tend to follow a regular pattern of evolution. While very different in their modelling and in their methodology, so-called industry life cycle theories make the common underlying assumption that the rate of technological knowledge obsolescence tends to decrease over time, thereby inducing a decreasing rate of entries. These authors propose different arguments to justify the claim that investments in process innovation will dominate over time, therefore increasing new entrants' hazard of survival and incumbent firms' leadership. Empirical studies show that this evolution pattern is characterised by a shakeout process whereby

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the rate of exit dramatically exceeds the rate of entry leading the industry to a higher level of concentration (Gort and Klepper, 1982, Klepper and Graddy, 1980, Klepper and Miller, 1995, Klepper and Simons, 2000). Under these conditions sectoral dissimilarities would be due to the different stages of life experienced by industries.

This thesis, while corroborated by empirical studies, has been criticised for not applying in other cases. In particular when products are based on a complex technology (Miller et al. 1995, Fransman, 1999, Bonaccorsi and Giuri, 2000) the shift from an entrepreneurial to a routinised regime of innovation cannot be taken for granted (Malerba and Orsenigo, 1996). Indeed, Klepper (1997) recognises that there are some industries where the model does not apply for different reasons related to the increasing division of labour.

The aim of this article is to show that the weaknesses of industry life cycle theories lay in the assumption that the rate of technological knowledge obsolescence necessarily drops over time. This is obvious in the radical invention version (Jovanovic and MacDonald, 1994) where the only determinants of industry evolution are time and success of adoption. In the dominant design version, the shift from product to process innovation is also an *ad hoc* assumption to impose the rate of knowledge obsolescence to drop radically when a *de facto* standard emerges. But this is also true in Klepper's version. Indeed, while the change of firms' incentive to invest in process rather than product innovation is endogenously determined, the model relates process innovation to a decreasing rate of knowledge obsolescence. This may not be the case, however, when process and product innovations are complementary. Furthermore, this article argues that product and technology should not be assimilated when they have their own pace of evolution. In particular, *'system products'* or modular products are based on several technologies that have different trajectories which are likely to modify the system's design regularly. Here, it is very likely that knowledge dynamics prevent any shakeout.

I will illustrate this argument by the case of the semiconductor industry whose dynamics depart radically from the life cycle predictions. First, a broad observation will show that the number of actors has not reduced over time and that shakeout has not occurred since exits have always more than compensated by new entries. Furthermore, as Filson (2000) notices, the rate of product innovation does not diminish, the rate of cost improvement is not always highest later in the life cycle, and whilst variable and fixed cost tradeoffs tend to occur, they do not always involve decreasing variable costs and increasing fixed costs.

The paper focuses on three different products families; namely, DRAMs, Microprocessors and ASICs that all rely on the same manufacturing technology. It is emphasised that the life cycle pattern of evolution seems to apply within product generations (in DRAM) or considering each design trajectory (particularly in microprocessors). But at industry level, the different life stages of products, and the systematic emergence of new competing design trajectories maintains a high level of knowledge obsolescence that prevents the occurrence of shakeout.

The rest of the paper is organised as follows. Section 2 reviews the literature on the evolution of market structures emphasising the underlying role of technological knowledge dynamics. Section 3 describes the semiconductor industry by distinguishing product design dynamics from manufacturing technology dynamics. It makes clear that an understanding of the way knowledge evolves, as described in Section 2, helps us understand the relationship between innovation and market structure dynamics. Finally, Section 4 discusses the conclusions put forward in Sections 2 and 3 and proposes some ideas for enhancing industry dynamics theory and make it more robust. This is presented as a suggestion for further theoretical and empirical work..

2. Knowledge evolution, technological change and Industry life cycle

Industry dynamics models try to provide a comprehensive explanation of the evolution of market structures, that is the evolution of market shares, of entry and exit rates and of each firm's profit and productivity growth. One of the central interests of this investigation is to understand whether there are general principles that condition the process whereby firms enter, grow and exit. A positive answer would help us to understand how and why barriers to entry change and would provide a useful heuristic for decision-makers both at strategic and policy levels. A growing attention is dedicated to so-called life cycle theories describing a similar pattern of evolution across industries. Two complementary discussions are of interest: 1) is this pattern is really relevant for all industries? 2) what is the explanation for such a pattern to occur? Section 2.1 will briefly review the different theories of industry life cycle and will try to make clear the arguments showing the limits of its application. It will also stress the assumptions implicitly made on knowledge dynamics. Section 2.2 will criticise these underlying assumptions and will try to propose a wider view of the impact of knowledge systems' evolution on industry dynamics.

2.1. Shakeout and non shakeout patterns of industry evolution

A. Industry life cycle theories

A growing body of theoretical contributions adopt a common representation of industry evolution from birth to maturity. They describe industries evolving from a formative stage, characterised by an increasing number of firms and by the instability of market shares, to maturity characterised by a shakeout whereby the rate of exit increase leading to a an eventual concentrated mature market (Jovanovic and MacDonald, 1994, Klepper, 1996, Klepper and Simons, 2000). These arguments are grounded on a series of empirical studies that corroborate the existence of common evolutionary features across industries. (Gort and Klepper, 1982, Klepper and Graddy, 1990, Utterback and Suàrez, 1993, Agarwal and Gort, 1996, Klepper and Simons, 2000). They also recognise the central role of technological change in the spiral of firms' advantage in industries with shakeouts (Simons, 2001). Their common view is that in the formative stage the rate of product innovation is higher than the rate of process innovation but over time the rate of process innovation increases sharply, thus reducing the structure of production costs, which eventually causes shakeout.

There is no common consensus, however, on how innovation affects firms' strategic decisions. The debate concentrate on the question whether this pattern of evolution is due to intrinsic characteristics of technological knowledge evolution or whether it is essentially due to firms' choices induced by the evolution of market conditions. A first argument considers the emergence of a dominant design as the main reason for firms to shift from product to process innovation[1]. A series of case studies in the automobile industry (Abernathy, 1978, Abernathy et al. 1983), on transistors (Anderson and Tushman, 1990), on PC software (Abernathy and Utterback,1978, Utterback and Suarez, 1993), support this idea. The dominant design theory is heavily related to technological knowledge considerations. The early stage of industry life is assimilated to an experimentation phase with high opportunities and intense design competition resulting in product innovation and in a high level of turbulence. As Anderson and Tushman (1990) explain, this infancy stage results from a technological breakthrough that gives rise to opportunities for developing competing technological trajectories. But at some point in time a dominant design emerges as a *de facto* standard making investments in process innovation more profitable than product innovation. As Sahal (1981) showed, once the dominant design (or the technological guidepost) is adopted, innovation can be dedicated to incremental improvements increasing the expected return of R&D -because more predictable and less risky. More precisely, competition is progressively concentrating on costs improvement rather than on quality improvement, giving rise to scale, scope economies and learning effects, therefore providing a competitive advantage to those firms that developed or adopted the selected design very early.

Indeed, as they take the lead of the market (because consumer demand shifts toward the standardised design), less profitable firms exit and barriers to entry set up. The combination of a fall in entry and a rise in exit results in a shakeout process. As a consequence, the emergence of a standard design increases hazards of product innovation investments so that incentives to invest in process innovation rise. Then, opportunities for entry slow down and survival hazard is lower for early adopters of the dominant design and higher for late adopter that cannot catch up along the learning curve. Eventually, as the technological paradigm dries up, expected return on R&D tends to zero and the industry progressively goes to maturity that can drive to death or to stable structures such as fringe oligopoly according to the nature of demand structure (cf. Caves and Porter, 1977).

Jovanovic and MacDonald (1994) propose another story to explain shakeout. Building on the example of the US tyre industry, their model holds in a partial equilibrium environment whereby the rate of entry is directly driven by expected profits so that it tends to decrease regularly until the expected profit is nil. Then, an exogenous radical innovation affects the equilibrium state of the industry by opening up new innovative opportunities and changing the minimum efficient scale, thereby raising new barriers to entry. Consequently, given heterogeneous capabilities to exploit efficiently these opportunities, and because the timing of entry affect firms' technology-related experience[2], successful innovative firms enjoy lower unit costs than those firms that keep

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[1] Process innovation is of a cost improvement kind (and thus tend to reduce the average market price) whereas product innovation is supposed to be quality oriented and tends to increase product's added value, that is customers' satisfaction and thereby their willingness to pay for the product.

[2] Incumbents firms that entered before the technological change and that successfully adopt the new technology have a competitive advantage because the enjoy one period of innovation more than post-

the older technology and grow faster to the optimal size. This obliges firms that failed to adopt the new technology to exit, accentuating first mover advantage and the shake out process. Then, shakeout is viewed as an equilibrating mechanism that naturally drives the industry towards the pre-invention exit rate. Here technological knowledge dynamics does not play a direct role in the pattern of evolution. However, the underlying assumption is that after the radical innovation occurred, technological knowledge is immediately stabilised so that competition is driven by asymmetries on access to knowledge rather than on knowledge creation so that costs improvements is the unique factor of driving the industry back to the equilibrium.

Beyond the lack of explanations on the conditions that determines firms' capabilities, (such as age or size), Klepper and Simons (2000) reject this interpretation because of its unrealistic assumption about the impact of an exogenous technological shock on the competition process. Additionally, they convincingly show that the actual US tyre industry dynamics is not consistent with Jovanovich and MacDonald model. Rather, a third interpretation is given. Klepper (1996) recognises that industry life cycle cannot only be attributed to an exogenous event such as the emergence of a dominant design. He notices that many industries had no dominant design, so the choice between product innovation and process innovation is not exclusive since companies are most of the time continuously investing in improvements of production process from birth to maturity.

Klepper (1996) develops a model that does not postulate any exogenous technical change. The author considers that shakeout is essentially induced by the endogenous evolution of expected returns to product R&D and to process R&D. He actually ascribes shakeout to the natural (convex) learning curve phenomenon coupling cost reduction and the level of output produced. Firms are endowed with different capabilities (randomly allocated) that they can use to product differentiation. At each period, they have to allocate their R&D resources between product and process innovation regarding their expected pay-off. Product innovation attracts new customers that are willing to pay more for the new product but then keep stuck to this product that becomes a standard product in the following periods[3]. As the unit cost reduces with size, there is a threshold (size) after which earlier entrants have more incentive to engage in process innovation than in product innovation (which expected returns are independent of firm size). Eventually firms that have not achieved the critical size exit and the industry achieves its phase of maturity. More generally, as industry evolves and the market grows the unit cost of a standard product tends to drop so that process innovation becomes more profitable than product innovation, which then only attracts a small fringe of the market.

B. Non-shakeout patterns of evolution

This model has been tested, and considered convincing, by Klepper and Simons (2000) against the exogenous hypotheses and particularly against the model of Jovanovic and

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innovation entrants. As a consequence, the hazard of exit rate is lower for thos incumbents that for later entrants, even thought they both succeeded in their technological adoption.

[3] The model relies on the assumption that product innovation attracts new customers (and thus increases the size of the market) that are incorporated into the standard product's demand at the following period. Then the standard product's demand increase is proportional to product innovation.

MacDonald (1994). It can hardly account, nonetheless, for all industry patterns of evolution. A series of empirical work have shown that certain product characteristics prevent any shakeout pattern to occur (Nelson, 1994, Miller et *al*. 1995, Malerba and Orsenigo, 1996, Klepper, 1997, Bonaccorsi and Giuri, 2000, Simons, 2001). Several explanations are given for the absence of shakeout, often linked to the nature of technological change[4]. Klepper (1997) actually recognises that some industries do not experience any shakeout pattern in their evolution. He notices that this is very likely to happen

- if there is an increasing firm specialisation over time favouring the emergence of a hierarchical division of labour (such as petrochemical industry where specialised engineering firms emerge regularly); As Arora (1995), Arora et al (1999, 2000) explain, the emergence of downstream specialists is developing with increasing number and size of markets for technologies favoured by patenting and licensing protections.
- when there is a division of labour between technical specialists and manufacturing/marketing firms (such as X-Ray, nuclear imaging, ultrasonic, computed tomographic, magnetic resonance imaging instruments, automatic teller machines, etc.)
- in case of firms specialisation based on fragmented submarkets, with firms differing considerably in the mix of submarkets serviced (business jets, lasers,…). Once again this can be explained, as in the case of the Laser industry, by the increasing vertical and horizontal applications for multi purpose technologies generally analysed as science based industries (cf. Freeman, 1982, Pavitt, 1984, Nelson and Rosenberg, 1993).

Bonaccorsi and Giuri (2000) argue that two fundamental reasons for non-shakeout patterns of evolution are 1) the violation of appropriability and 2) the absence of increasing returns. Both of them result in low incentive to invest in R&D and thus prevent any accumulation process. Furthermore, they explain that vertical specialisation between product and process R&D and the manufacturing stage is a central cause for violation of appropriability. "Vertical separation creates a market in-between the originator and the users of an innovation, and therefore prevents the monopolistic appropriation by any of the users" (ibid. p. 851). While the link between vertical specialisation and non-shakeout pattern is relevant, the lack of appropriability of R&D does not appear as an obvious cause to us. In particular, as Arora and Fosfuri (2000) and Arora et al. (2000) show, vertical specialisation tends to be favoured by better appropriation conditions made possible by patenting[5] and licensing for example. I will

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[4] The absence of technological change can also justify non shakeout patterns (cf. Simons, 2001).

[5] Bessen and Maskin (1999) show how vertical specialisation emerge in case of weakness of patent protection. Because innovation is sequential (i.e. each successive invention builds on the preceding one) and complementary (i.e each potential innovator takes a somewhat different research line and thereby enhances the overall probability that a particular goal is reached within a given time), it is argued that competition can increase firms' future profit thus offsetting short-term dissipation of rents since imitation may promote innovation such as in software and computer industries. Since this argumentation is receivable in a social welfare context, one can wonder if this is a good description of companies' strategy

show that this particularly true for the semiconductor industry that experience both increasing return on R&D and do not suffer from hold up risks due to weaknesses in knowledge appropriability.

More convincingly, Sutton (1998) and (Argarwal, 1998) observe that shakeout does not occur in industries where several technological trajectories compete to supply products dedicated to independent markets. Sutton notices that life cycle models necessarily assume the stability and the homogeneity of both the evolution of technology and of customer tastes after the mature stage started. He builds his analysis on two basic principles: the "survivor principle" saying that firms do not pursue loss-making strategies and the "arbitrage principle" saying that there will always be a firm to take a profitable opportunity. Sutton's bound approach predict that the relationship between R&D intensity and the level of concentration in an industry will essentially depend on the number of technological trajectories and their associated submarkets. More precisely the level of concentration will depend on R&D effectiveness[6] and on the number of independent technological trajectories that produce poor substitute goods.[7] In other words, his bound approach define the necessary conditions for sustainable economies of scale or learning effect to occur and thus for a minimum level of concentration in a specific industry. But, defending the idea that technology and market structures are co-determined, he is reluctant to provide any prediction on the evolution of these two dimensions. In particular, he emphasise the importance of technological shocks or changes in the pattern of tastes that modify consumers' willingness to pay for the new product inducing a "profitable deviation" in the industry. In the photographic film industry for instance, Sutton shows that the life cycle model remains a good representative of industry's history from 1870 to 1940. But the introduction of a product innovation (colour film) modified this trend and resulted in a raise of consumers' willingness to pay and therefore destroyed the model's predictions. Malerba, (1999) also observe that computing and telecommunication industries, are very likely to depart from the life cycle propositions. The reason remains the nature of technical change that modify technical linkages between two different industries allowing network effects –that have the same analytical consequence as learning effects (cf. Gruber, 2000).

Summing up this discussion, we can conclude that life cycle theories apply very well in those mass market industries whereby first innovation affects products dedicated to markets endowed with relative homogeneous preferences and second the production process tends to standardise over time (i.e. characterised by strong scale and scope economies) and innovation tends to become of routine and cumulative natures (learning effect). On the other hand, life cycle theories hardly apply in case of sustainable competitive technological trajectories, in particular in those CoPS industries whereby products encompass an great number of technologies whose evolution often affect the product design dynamics. As Patel and Pavitt (1997), Pavitt, (1998) and Brusoni et al.

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researching for sustainable competitive advantages. More precisely, the authors consider patent but not licensing, which Arora et al. (2000) demonstrate to be a promoter of knowledge spillovers.

[6] Represented by $1/\beta$, which is determined by the relation between R&D investments and technical performance and by the impact of technical performance and demand growth.

[7] Noted σ and determined by the level of scope economies in R&D and the level of substitution in consumption of produced goods.

(2000) have shown the evolution of products and of technology are very likely to be dissimilar in complex products industries. As a consequence, a consistent theory of industry dynamics should consider two complementary observations. First, the boundaries of an industry are not fixed, in particular when products rely on several complementary technologies that have their own pace. Second, industry dynamics should take into account the strategic impact of down stream markets in particular in those modular products where the technological trajectory is dependent on the relation between a technology and its application in a specific product. In the next section, it will be argued that the study of knowledge dynamics can provide useful framework for analysing the link between the nature of technical change and the evolution of market structures.

2.2. Products, technology, and Knowledge obsolescence

A. Knowledge obsolescence and shakeout

As stressed by Nelson and Winter, (1982), innovation relies on the capability to generate new knowledge. Further, Winter (1987) notices that the nature of technological knowledge varies across industries because they exhibit different levels of specificity, complexity, tacitness and cumulativeness. Indeed, capabilities to generate new knowledge are strongly dependent on the nature of problems to be solved and rely on complex interactions between science, technology and socio-economic institutions (Nelson and Winter 1977, Kline and Rosenberg 1986, Rothwell 1992, 1993). And this heterogeneity of intrinsic technological knowledge characteristics gives rise to persistent inter-sectoral differences (cf. Pavitt, 1984 and Pavitt et al. 1987).

Neo-Schumpeterian scholars (Nelson and Winter, 1977, 1982, Winter, 1984, Audretsch, 1995, Malerba and Orsenigo, 1996) have tried to operationalise such remarks by relating those observed differences in market structures to particular regimes of innovation or 'technological regimes'. A technological regime is a particular combination of opportunity and appropriability conditions, degree of cumulativeness of technological knowledge and characteristics of the relevant knowledge base (cf. Malerba and Orsenigo, 1993, 1996). Two different regimes are distinguished: A turbulent -or entrepreneurial- technological regime (with low appropriability conditions, low cumulativeness of knowledge and rich technological opportunities) and a stable -or routinised- technological regime (with high appropriability conditions, high cumulativeness and poor technological opportunities). This position does not actually refute the life cycle model since it can be argued that technological regimes may change as the industry evolve (Acs and Audretsch, 1993, Audretsch, 1995, 1997, Malerba and Orsenigo, 2000). It does not assume, however, that the shift from entrepreneurial to routinised regimes is systematic, which would suggest a systematic evolution of the underlying knowledge conditions (Audretsch, 1995, Agarwal and Audretsch, 2000).

More precisely, be it by the emergence of a dominant design or an endogenous shift in firms' incentives, shakeout is necessarily linked to the shift from a knowledge obsolescence regime to a knowledge accumulation regime. A high rate of knowledge obsolescence tends to favour new entry and turbulent market structures (Winter, 1984, Agarwal and Gort, 1999): It necessarily reduces expected returns on R&D investments and weakens technological barriers to entry (Sutton, 1998). Conversely, when improvements are

"based on human and physical capital investments that [are] not rendered obsolete by subsequent major product innovation" (Klepper, 1996 p.563), then learning effects are playing a central role in market structures' evolution[8].

B. Is there a knowledge cycle?

This systematic stabilisation of technological knowledge dynamics is consistent with the 'innovation cycle' argument (Nightingale, 1998) based on innovation *studies in vivo* (Vincenti, 1990, Nightingale, 1998, Stankiewicz, 2000). This cycle starts with an initial, ill-defined conception of a problem. Once the general problem can be expressed through meaningful questions it takes the form of a specification process that allows engineers to concentrate on more sophisticated hypotheses and specific sub-problems (Orsenigo et al 1999). Thus, accepted solutions to the general problem can be viewed as a fundamental knowledge, i.e. as a cognitive background (sometimes implicitly used) that enable engineers to recognise and define more specific problems (Vincenti, 1990, Nelson, 1991). This fundamental or generic knowledge (Nelson, 1991) forms a *design space* (Stankiewicz, 2000) that generates "a certain universe of technical possibilities" (ibid. p. 235). Then the *design space* expands and get more and more structured by stabilising the relations between recognised problems and known solutions.

Knowledge systems can therefore be conceived as hierarchical or modular organisations (Henderson, 1992) or a quasi-decomposable system (Simon, 1926) where fundamental or generic knowledge is distinguished from specific or context-specific knowledge (Nelson, 1991, Iansiti, 1998, Dibiaggio, 1998, Constant, 2000). Fundamental knowledge concerns domain-specific and not product-specific knowledge (Iansiti, 1998, p.10). Domains are self-contained, fundamental disciplines independent of the immediate context of the product. Specific knowledge is knowledge dedicated to a specific problem[9] and is directly embedded in products or systems. It is context dependent since it has to adapt to the specifications and the characteristics of a specific technical system. Context dependency arises because engineers often lack a complete understanding of the technology. Firms do not necessarily need to understand the scientific principles underlying the technology they use to produce goods, methods or processes (Arora and Gambardella 1994). This is possible because once fundamental knowledge is winnowed and recognised as robust enough, standardisation makes it implicit, i.e. not used explicitly but as a background. More than a dominant design, knowledge base stabilisation should be understood as a 'normal configuration' (Vincenti, 1990) that provides a common tacit

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[8] Tushman and Anderson (1986), who distinguished competence enhancing and competence destroying innovations, had already made put forward the consequences of knowledge obsolescence on market structure.

[9] Iansiti (1998) labels the context dependent knowledge 'system knowledge' because this knowledge needs to perform integration tasks, which is not captured by fundamental domains. As an example, while results of experiments with protocol description are published, replication may be very difficult. The author takes the case of the TEA laser provided by Collins (1982) as an illustration. He describes how replication of the published research of the original innovator was extremely difficult to achieve.

understanding of a technological domain (Nightingale, 1998)This standardisation process gives rise to highly cumulative learning, knowledge system develops itself around a rigid structure and exhibit strong learning effects at industry level. “At higher levels of the hierarchy, hypotheses tend to stay relatively stable, since their falsification occurs over a relatively long time scale, being based on the falsification/selection of hypotheses at lower levels of generality” (Orsenigo et al. 1999, p. 6)..

Of course the counterpart of this innovation cycle on the industry structure's side is an increasing role of path dependency in innovative activities, the induced shakeout process leading to a higher level of concentration and a stabilised division of labour across companies as predicted by industry life cycle models. But this innovation cycle, again, assumes a progressive stabilisation of architectural knowledge, which may not be verified. In particular, persistent instabilities are recurrently observed in case of intensive system integration dynamics occurring in complex products architectures (Miller et al. 1995, Singh, 1997, Iansiti, 1998, Bonaccorsi and Giuri, 2000, Brusoni and Prencipe, 2001). This modularity breaking process is generally caused by repetitive dynamic system integration (understood as the ability to explore alternative paths of product and process innovation, Brusoni and Prencipe, 2001) whereby initially independent bodies of knowledge developed in autonomous technological modules or even independent domains are linked and made complementary. As a consequence the design space happen to be and the level of knowledge obsolescence remains high (cf. Dibiaggio, 1998).

Modularity breaking is generally related to innovations initially dedicated to adapt existing products to new applications and ended by important structural change in the underlying technology. This can be applied vertically such as the use of laser in surgical scalpel, copiers, semiconductors, etc. that strongly affected the laser technological trajectory (Rosenberg, 1982, Grupp, 2000) and imposed the development of new competencies and the adaptation of the whole production process. It is more often horizontally by using a well-established technology in radically new domains (one of the main source of firms' diversification). Chemical industry was born in 1774 with the need of textile industry to improve productivity of washing and laundering. Scheele discovered Chlorine in 1774 and the first bleach manufacture in 1777. But laundering was requiring products based on soda as well, whose production process had been developed by Leblanc in 1776. Then the new chemical industry really emerged with its application for the implementation of new materials such as rubber in the beginning of the 19th century and later plastics. An other example is the introduction of software in telecommunication switches. This caused a major impact on the knowledge base of telecom equipment manufacturers that became software programmer (cf. Fransman, 1998). Each time, the trial to adapt a technology to new applications induces innovations (sometimes radical) because imperfections and context contingencies requires new knowledge that open a new field of research and eventually new industrial developments. And each time, this process of integration of new knowledge constitutes opportunities for new comers

Of course this knowledge argument is not necessarily consistent with the traditional explanations of non-shakeout patterns as a result of the lack of increasing return on R&D.

3. The case of semiconductors

As well described by the literature (Tilton, 1971, Dosi, 1984, Malerba, 1985, Gruber, 1994, 2000, Langlois and Steinmuller, 1999), the industry started in the fifties after the invention of the transistor by Bardeen, Brattain and Shockley in 1947, driven by military demand. It initiated the era of solid-state electronics that framed the semiconductor industry evolution. A series of inventions (vacuum tube in 1906, point contact transistor, 1947, junction transistor, 1948, diffusion-oxide masking- photo process, 1954, the integrated circuit in 1958 and the planar technology in 1959) stabilisation of an innovation trend within a technological paradigm as explained by Dosi (1982). In fact, two foundational inventions (Jack Kilby's invention of the integrated circuit at Texas Instruments coupled and the planar process invented by Robert Noyce at Fairchild) permitted the beginning of a long trend of cumulative process and product innovations contributing to a miniaturisation trajectory[10]. In 1962, the industry reaches its first billion dollars with the emergence of the mainframe industry. In the seventies the MOS technology (Metal Oxide Semiconductor invented by Intel in 1962) became the manufacturing technological standard[11] and favoured incremental innovations. Then a series of process innovations improved the importance of scale economies and of learning effects (Sutton, 1998). This suggests that we have the conditions for the industry life cycle to apply.

However, one can observe significant deviations in the industry history. In the early fifties, thirteen U.S firms were competing on the transistor market. Eight incumbents were vacuum tubes producers[12] and five new entrants were specialised in electronics (e.g. Texas Instruments, and Fairchild Semiconductor). Not surprisingly those successful entrants had all close connections with Bell Labs. The invention of the planar process and of the integration circuit induced a second wave of entries in the beginning of the sixties and changed the structure of the leadership. The generalisation of MOS production techniques (invented by Intel in 1962) induced a third wave of entry in the seventies, partly explained by the Fairchild's inability to develop its own MOS capabilities and to retain his engineers that went to set up new specialist firms[13] (Tilton, 1971). Moreover several different incompatible manufacturing techniques were developed (CMOS, PMOS, NMOS, ECL, TTL, and S/LD TTL) mainly derived from the MOS technology, preventing the expected standard effect. The industry remained quite well structured though, dominated by U.S companies such as Texas Instruments, Fairchild and National Semiconductor, that is by early adopters of the IC/planar technology.

Another series of new entries occurred in the seventies with the decision of Japanese firms to become serious competitors. These entries benefited from a new generation of

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[10] After, the integrated circuit (IC) came medium scale integration (MSI) in the sixties, then large scale ;integration (LSI) in the seventies, very large scale integration (VLSI) in the eighties and ultra large scale integration (ULSI) in the nineties.

[11] Another technology (digital bipolar) is still available and used for specific applications. MOS devices are slower than bipolar ones but they consume less power and generate less heat.

[12] Among which General Electric, RCA, Raytheon, Sylvania, Philco-Ford and Westinghouse.

[13] Schaller (1996) reports that at least 150 companies, including Intel in 1968, were spawned by Fairchild.

memories (16K DRAM) using CMOS (Complementary MOS) technology[14]. This gave them a competitive advantage that became visible for the 64 K DRAM generation (cf. Langlois and Steinmuller, 1999). Nonetheless, the emergence of the microprocessor, introduced by Intel in 1971, gave rise to a new market trend in the eighties with the explosion of the personal computer. This modified the leadership structure of the industry but did not open the market to new comers. In the late eighties a new series of product innovations in logic chips affected again the trend towards maturity. New lines of microprocessors (RISCs, DSPs) were introduced and gave the opportunity to open the door to new entrants (mainly small fabless companies such as MIPS and SPARC) and to modify the semiconductor raking (in particular T.I., the worldwide leader in DSP came from the seventh to the third position).

The nineties saw two new changes in the industry. First, after their late arrival, Korean firms (e.g. Samsung, L.G and Hyundai) became first order players by taking the lead in DRAM. Unlike other waves of entries, this resulted from a long period of catching up by cumulative improvements and of regular adaptation thanks to alliances with advanced O.E.M (cf. Choung et al. 2000)[15]. Second, the specialisation of small firms in IP markets favoured important product innovations in logic chips and in ASICs. With the improvement of design tools, this permitted the entrance of systems integration companies based on a 'leapfrogging' strategy: they try to impose new products (“the killer application”) that could become a standard in nascent and fast growing markets.

The beginning of the 21st century is characterised by a new trend of technological change with devices line widths reduced from 0.18-micron to 0.13-micron and based on new production processes -Silicon On Insulator (SOI), new metalisation technologies -silicon germanium (SiGe) and copper (cu)- more fitted for growing markets' applications. At product level, a new series of innovations is coming in the ASICs' family pulled by new needs of growing markets and the generalisation of embedded systems that increases integration possibilities. In particular, System-on-a-chip solutions appear to be more cost-effective for specific applications such as mobile phone handsets, telecommunication, base stations, set top boxes etc. It is worth noting that this design solution is made possible and useful thanks to improvements on line width that justifies further integration in chips.

This pattern of evolution seems to depart radically from the life cycle model. Indeed, figure 1 shows the absence of shakeout, a regular increase of the number of players and a sustainable rate of small firms. Further, Filson (2000) notices that the rate of product innovation does not diminish over time, the rate of cost improvement is not always higher later in the life cycle, and whilst variable and fixed cost tradeoffs tend to occur they do not always involve decreasing variable costs and increasing fixed costs.

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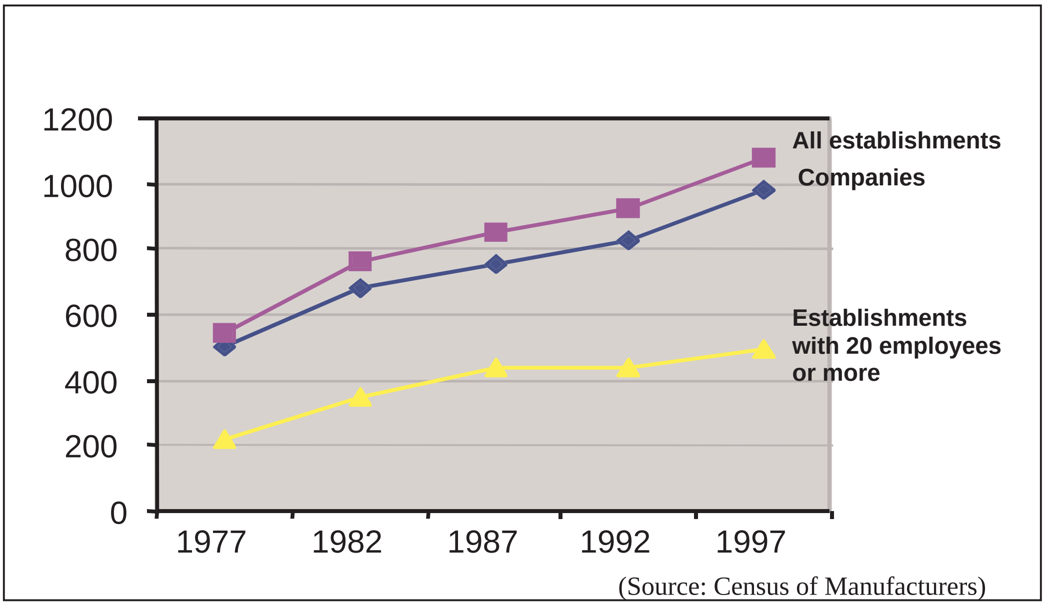
[14] The MITI funded a large part of the Very Large Scale Integration program, which contributed to the emergence of a Japanese leadership in the late seventies and in the eighties (98% market shares of the 4M DRAM market and 80% of the memory market were owned by Japanese firms in 1990).

[15] Van de Gevel (1997) does not agree with this view and argues that the Korean success is by no means related to upgrading experiences nor by the creation of a knowledge based. Rather he considers that it was permitted by simple comparative advantages thanks to high market prices imposed by the Semiconductor Trade Arrangement (STA) between Japan and the US. To see the impact of the STA on Japanese firms' strategy, cf. Park, (2001).

I will show, however, that this is the result of a never ending expanding industry where each product actually experiences a classical life cycle but where scope economies in design systematically affect the products' design space promoting radically new products that subsequently encounter new markets and increasing the rate of knowledge obsolescence. Further, I will emphasise that learning effects, when very high such as in memory chips, do not necessarily justifies incumbents' leadership for two reasons. First because the existence of spillovers give the opportunity for new entrants to upgrade when they accept to pay sunk costs. Second because the sustainability of product innovation makes it more profitable for incumbents to exit markets with lower added value. Finally, products and technology cannot be assimilated. They experience different innovation trajectories even though it is clear that rather than competing, investments in process and in products improvements are complementary. More precisely, product innovations happen to be strongly dependent on improvement in manufacturing technology.

To make these ideas clear I will describe the gap between the evolution of the design space at products level and the innovation dynamics in the underlying semiconductor technology. Then, I will emphasise the different impacts of this gap for three different products family, namely memory chips, logic chips and ASICs. Finally I will try to explain the strategic consequences of these differences at firms level and on industry evolution.



(Source: Census of Manufacturers)

Figure 1: Evolution of the number of Companies and of establishments

Semiconductor technology evolution:

Memory chips, logic chips and ASICs are semiconductor products based on the same underlying technology. Chips are produced by batches on silicon wafers, which are cut and packaged to make single chips. Improvements in production are measured by productivity gains. On the one hand, productivity relies on scale economies permitted by the dramatic and regular increase of wafers size and by the reduction of cell area that both permit to increase the number of chips on a single wafer[16]. On the other hand, productivity critically depends on static and dynamic increasing returns. Indeed, scale economies are huge (and increasingly so) in the production of semiconductors: chips production facilities experience an exponential cost evolution. This follows what has been labelled the Rock's law[17] that predicts that the cost of a plant will double every four years, given that a leading edge plant's life cycle lasts between three and five years only. R&D investments tend to rise also sharply. As we shall explain later, because technological leadership critically determines future market shares several products experience an escalation in R&D spending as described by Sutton (1998). However, unlike Sutton's assumption, this is occurring despite the persistence of competing technological trajectories (in design) making different products potential substitutes. This is due to the increasing division of labour between manufacturing and design. Whilst the number of manufacturer tend to decrease sharply (often translated by join ventures to share investments in new plants), the number of design companies are increasing more than proportionally.

Dynamic increasing returns are also very important in the competition game. First, yields' improvement (i.e. the percentage of chips that are free from defect on a processed silicon wafer)[18] determines the productivity of the lot of wafers. Innovations in production techniques are generally considered as process innovation since they improve productivity of all product families. Yields improvement are dependent on learning-by-doing and make the learning curve a strategic dimension of competition.

These evolutions are made possible thanks to a series of complementary innovations from equipment to physical materials. As mentioned above, the MOS technology gave birth to a series of co-evolving technologies (PMOS, NMOS, ECL, TTL and S/LD TTL) that regularly improved productivity. They were eventually rendered obsolete by the CMOS technology introduced in the eighties and currently accepted as a standard[19]. Consequently, CMOS provided the well-known benefits of standards in production such as design experience, simplicity and continuous improvements. It therefore dramatically contributed to improve the yields.

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[16] This is measured by the technology node (nm), i.e. the minimum metal half-pitch. The average reduction rate in this feature size is very high. It was approximately 11% per year in the time interval 1990-1995 (about 30% reduction/three years) and 16% per year in the time interval 1995-1999 (about 30% reduction/two years). Following the hypothesis of a two years cycle, it is expected that 130nm manufacturing will replace the 180 nm one in 2003 (Sematech). Wafer size, in itself, experiences a nine-year cycle (then the year average growth rate is approximately 13%). It is expected to reduce to a seven years cycle. From 51 mm in 1960 the new wafer generation which is being implemented will produce wafers of a 300mm area. The move from the 200mm generation to the 300mm generation will more than double the number of chips on a single wafer.

[17] Arthur Rock financed the Intel venture. Rock's law is often quoted as Moore second's law (Schaller, 1996).

[18] Yields tend to be very low in the early development stage (sometimes less than 1%) and then rise regularly up to 90%. The yields have been one of the most competitive advantage of Japanese firms over U.S. firms in the eighties and the nineties.

[19] This standardisation is motivated by the increasing number of international alliances in order to reduce firms' investments in semiconductor facilities.

Unlike traditional oppositions between process and product innovations, here innovations in lithography systems and a ten years investment (from 1985 to 1995) in capital and R&D spending growth centred on CMOS technology contributed to a sustainable trend of product innovations. Moreover, there are clear relations between fundamental discoveries relying on science findings.[20] In devices, innovation is driven by the reduction of line width, which conditions the number of transistors in a single chip. The higher the number of transistors, the higher the number of operations a device will be able to accomplish in a given period of time.[21] Line width has been reduced at an exponential rate: from 12-micron in the late sixties to 0.18-micron / 0.13-micron today. This contributed to make Moore's Law sustainable.[22]

In other words, this description of innovation trend in manufacturing technology entails every element that should result in a maturation process that is expected to generate shakeout: a dominant technological trajectory, strong scale effects with increasing R&D and investment costs, strong learning effects. The technological knowledge base for manufacturing chips (wafer manufacturing, chip manufacturing, packaging and tests) is stabilised and can be considered as evolving along a known trajectory. In other words, technological knowledge is cumulative and is not really subject to obsolescence.

Products evolution

This section will put forward a distinction between products whose innovation heavily relies on technological progress such as DRAM and products whose innovation depends essentially on design such as logic chips and ASICs. Because design technology develops along with several competitive trajectories, the rate of knowledge obsolescence is high so that sustainable competitive advantages are weak. It will be shown, however, that in logic chips this argument must be moderated. Whilst logic chips are design intensive, there is cumulative experience in design's knowledge base but, because of scope economies in design, there is strong knowledge obsolescence in specific knowledge.

Memory chips (information storage devices), logic chips -Microprocessors (MPUs), Microcontrolers (MCUs) and Digital Signal Processors (DSPs)- and ASICs [23] (Application Specific Integrated Circuits) are three different product families relying on a

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[20] In particular, progresses in line width rely on innovations at physical level, which has been driven by the improvement of bulk materials properties and is now increasingly dependent on the physics of material interfaces between atomic scale films. Until recently, this research was based on the statistical properties of atoms distribution, it is now conditioned by the precise position of atoms as line width decreases. The possibility to reduce line width under 0.1-micron will need a radical change in materials with the expected use of biologic materials or/and quantum materials.

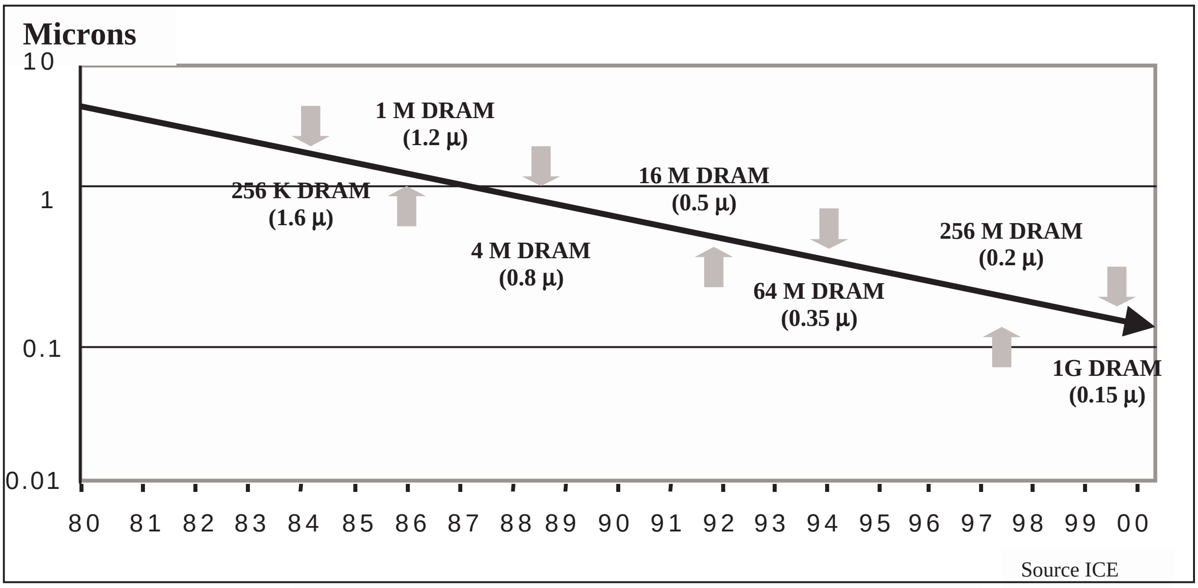
[21] This is why MIPS (million of operation per second) is another measure of Moore's law.

[22] Moore's law predicts a doubling of the number of transistors in a chip every year (every eighteen months since the seventies) at a constant unit price. In 1959, a chip encompassed only one single component, it integrates approximately ten millions today. Moore's Law happen to be an industry roadmap that provides common visions and expectations to all actors (Schaller, 2001) and thus can be considered as has a strong co-ordination power at industry and policy level (cf. Dosi, 1984).

[23] I will call ASIC all products that are dedicated to specific demand that cannot be supplied by standard products. I will integrate in this category pure hardware solutions, application specific embedded systems and system-on-a-chip designed around a core logic chip. A System-On-a-Chip integrates almost all aspects of a system in a single chip.

same production technology but requiring different design technologies. Those products have different life cycles and different competition rules. The first distinction is the characterisation of quality improvement (product innovation) for each product. This is partly due to the variability of achieved functions of each product after innovation has been implemented.

Memory chips[24] have a constant function over generations: they store data. Thus, product innovation is characterised by a new generation that increases the memory capacity of a device and the speed of operations[25]. DRAM (Dynamic Random Access Memory) are volatile chips, that is they temporarily store data, which they loose when power is turned off. Innovation in DRAM is directly based on manufacturing technology improvements. Again, productivity gains are directly dependent technology nodes wafer size and line width). Not surprisingly, DRAM capacities follow the Moore's Law and there is a close relationship between memory chips life cycle and technology life cycle (cf. Figure 2).



Source ICE

Figure 2: DRAM vs IC Feature Size Trends

This dependency on manufacturing justifies the importance of learning effects, scale economies and high sunk costs (Gruber, 1994, 2000). There is a low rate of knowledge obsolescence (relative to other products) between one generation to another[26] and price competition is very strong. Because Memory chips rely on stable knowledge base, the evolution of performances is not really an issue for competitors. DRAM is considered as commodity chips even though they can be dedicated to a specific application. Therefore

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[24] Note that there are different memory chips using the MOS production technology, such as DRAM, SRAM, ROM, EPROM, EEPROM, Flash, which exhibit different characteristics and thus different innovation trends and different product life cycles. We take the case of DRAM as a guideline.

[25] With DRAMs, capacity is multiplied by four for each new generation and by two with EPROMs but the interval of introduction between generations is twice as long for DRAMs (every 3 years) than for EPROM. (every 18 months) so that they both follow the Moore's law (cf. Gruber, 2000)

[26] This means that knowledge is cumulative so that knowledge developed for one generation is useful to develop the next one.

competition is mainly driven by cost improvements both within a product life cycle and between product generations. This is clearly illustrated by this micro industry life cycle: each new DRAM is introduced by a leading firm, which provokes a wage of entries (up to 20 producers) and a shakeout in the late stage of the product life cycle (figure 3). As a consequence, firms' behaviour is driven by a learning curve optimisation (Park, 2001).

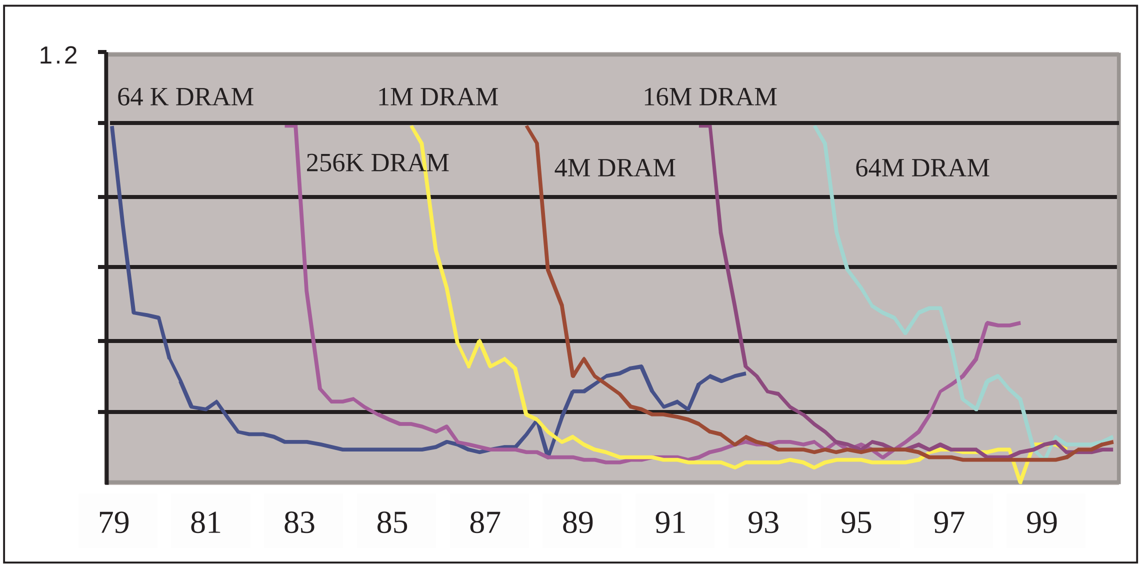

Figure 3: DRAM Herfindahl-Hirschman Index

Therefore, we have a perfect shake out pattern of evolution within each product generation. But this pattern is not obvious between generations. Intel introduced the first 1K DRAM in 1970. Birth was characterised by new entrants and then a dominant design emerged, followed by a shakeout process until maturity…in the seventies! Nonetheless, strong periods of turbulence have recurrently occurred. First in the seventies with the arrival of Japanese firms caused a strong exit rate of US firms (and Intel among them). Second in the eighties with the Korean firms that took the lead in the nineties and are the incontestable leaders today[27]. Over the last three years, the market experiences a new trend of concentration[28] with the arrival of Taiwanese players. In particular, Japanese firms tend to exit the market[29] (cf. figure 4) and Korean firms (Hyunday and LG) were urged to merge by their government. The US actors that had kept some shares in the DRAM market have decided to give up as well. In particular, Texas Instruments (sold its stake in DRAMs to Micron technology in 1998), Motorola (exit in 1997). In 1998, Taiwan already represented 54% of the foundry market and had already 12% market shares.

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[27] Samsung market shares signi ne fifth place.
[28] The top fi
[29] In particu of big alliances to

Those late comers are all characterised by a strong power to monitor complementary assets (mainly investments and foundry), to develop absorptive capacities and a competitive advantage (Ernst et al. 1994, Choung et al., 2000). Before, the arrival of Japanese firms, the industry was well structured around a dominant design and well-established dominant incumbents. Their success is essentially due to competitive advantage in manufacturing. Their strategy is to catch up in technology by entering the foundry market through international alliances and then diversify in DRAM, which does not require high design capabilities.

In a strategic perspective, the specificity of current DRAM market can be described as a sequential process: New comers enter the foundry market in order to develop capabilities in manufacturing technology, by creating alliances with DRAM incumbents. They usually build plants with the support of their government in order to cover sunk costs. Then they build their knowledge base to enter the DRAM market, which provides higher gross margins. But their strategy is to increase their market share by reducing the market average gross margin. Then incumbents face an increase of competition, which lowers their gross margin in DRAM. They then decide to exit and enter a higher gross margin market such as logic chips. In other words, once the fundamental knowledge is set up they try to develop specific knowledge in higher profitable markets that are more intensive in design.

Logic chips integrate different devices that to perform different generic and/or specific functions. New products are introduced approximately every 3-4 years and are characterised by an increasing information processing capacity and clock speed. Gate length and the number of interconnected layers are the most representative characteristics of performance evolution. Unlike memory chips, logic chips can have strong differentiation in their function. It is not a commodity that can be sold on a spot market. Three main products are generally distinguished. Microprocessors (MPUs) are the central processing unit of computer systems. Microcontrollers (MCUs) are computer systems contained on a single IC that are programmed to specific customer requirements. Finally, Digital Signal Processors (DSPs) are parallel processors used for high-complexity, high speed real-time computations in a wide variety of applications such as modems and digital cellular phones. Logic chips are more intensive in design and the nature of a product may change over generation. Because design adds value, this opens windows for vertical specialisation. Small companies with no facilities (fabless) can focus on design and propose innovative solutions and sell their IP as a patent or as a licence or outsource the downstream part of production to manufacturers. Product obsolescence is stronger than in DRAM (essentially for microprocessors) because inter-generation products are not substitutable. This explains network effects that products marketed earlier benefit as they become a standard (Gruber, 2000). A key strategic criterion, therefore, is time-to-market. Logic chips industry is less affected by learning effects (Gruber, 1994) mainly because the full cost is not only dependent on production costs but also on design.

Logic market, however, seems to be at least as stable as the DRAM one. Table 1 shows that Logic chips is a growing market increasingly dominated by Intel and where concentration tends to increase over time (the five leaders have an increasing market share over time 54.2 in 1987, 60.4 in 1991 and 65.1 in 1994 and the HHI in 1999 is higher than 0.3).

Company	1987	1991	1994	1999
Intel	20	27.2	39.1	45.5
NEC	14	10.9	7.4	3.9
Motorola	8	10.3	9.8	7.4
Hitachi	7	6.8	4.1	3
Mitsubishi	3.9	5.2	2.6	1.8
Toshiba	5.2	4.9	3	2.1
TI	3.3	3.5	4.1	4.6
AMD	?	3.4	4.7	3.5
Matsushita	?	2.5	2.1	1.9
Fujitsu	3.3	3	1.5	1.5
National	3.8	?	1.7	
Sanyo	2.4	?	?	?
Lucent	?	?	?	2
ST Micro	?	?	?	1.5
Other	29.1	22.3	19.9	
Total	100	100	100	
Total (value $M)	4,950	11400	24000	

(source: ICE/Dataquest)

Table 1: MOS Logic chips Sales Leader

Intel enjoyed an initial technological advance and took the lead immediately in 1971 with its first 4-bit microprocessor. Then a wave of entries occurred in 1975 when the microprocessor became mass market. The second source strategy of incumbents such as Intel, Motorola, National or Texas Instruments favoured new entries. Intel's market share in the 8-bit microprocessor market then declined until 1981 enjoying only 20% of the semiconductors market (compared to 65% in 1977) but still leading the market and keeping more then 60% of the microprocessor market. The industry knew another modification after IBM's decision to adopt the Intel's 16-bit 8086 for their computer. Intel regained its market shares and remains the incontestable leader so far (69% of the microprocessor market in 1992, 84% in 1996).

The dynamics of logic chips industry is interesting. First because exactly as in memory chips market (for different reasons though), there is an increasing concentration trend, but no shakeout. Second, because despite the market leader has experienced a sustainable competitive advantage over the last twenty years, this leadership is dependent on the market growth of PCs compared to other applications, which could be questioned in the following years.

Successful players, and particularly Intel in MPUs, built their advantage on a combination of process technologies and design competencies because of complementarities between design and manufacturing technology and because of the required capacities to remain independent and to be able to supply customers. But for sure, the distinctive competencies are made in design, which is specific knowledge. Each product (MPU, MCU, DSP) follows a specific design trajectory. And each design trajectory is mainly dedicated to a set of applications or even to a specific end product. This means, for instance, that Intel lags far behind Texas Instrument in DSPs design or behind ARM and MIPS in RISC design. It is clear that distinctive specific knowledge provide a sustainable competitive advantage: T.I has the equivalent leadership in DSP as Intel does in PCs, essentially because T.I. was chosen as the main Nokia's supplier. Then T.I could enjoy a faster learning curve and thereby could build a sustainable leadership in DSP specific knowledge. Almost every mobile phone has a ARM's RISC MPU.

However, this first mover advantage may be questioned because products are potentially substitute so that a new design technology could diversify in different application that used different products previously. A DSP and an MCU, for instance, can perform the same functions. Choices are usually dependent on tradeoffs such as MIPS (million of instruction per second) vs power consumption or on their performance in a specific integrated system. In other words, if there are learning effects in logic chips there are also scope economies in design that can permit to enter new markets and make previous specific knowledge in this application obsolete.

A good illustration is the history of the RISC architecture introduced by MIPS[30] in 1986. MIPS was a descendant of the Stanford MIPS project led by John Hennessy, one of the three pioneering RISC research projects of the early 1980's. The RISC architecture was simpler than the Intel's CISC architecture and the original R2000 contained just 110,000 transistors (compared to almost 300,000 for the Intel 386) and was six times faster than

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[30] MIPS stands for Microprocessor without Interlocked Pipeline Stages.

the Intel 386. Very early a series of companies converted their product line to RISC architecture (Hewlett-Packard, IBM,[31] Apple, Motorola Power PC). In 1987 Sun Microsystems developed an RISC based workstation. Later, IBM (1990) and DEC (1993) developed new machines based on a RISC architecture. The RISC architecture could not challenge Intel's CISC mainly for network effects due to IBM initial exclusive choice. But the RISC architecture enabled MIPS to develop new designs used by ASIC developers and system OEMs for use in emergent markets such as play stations, set top boxes, digital cameras, etc. RISC has definitely opened up a new (and competitive) trajectory that eventually permitted to develop new applications. Today, even Intel develop a new processor with a RISC architecture (licenced by ARM) for digital audio players.

One question is why learning spillovers do not generate "leap-frogging" and thereby annihilate any sustainable competitive advantage in knowledge. Indeed, spillovers mean that specific knowledge, which is firm specific, can very quickly be imitated by competitors. A second mechanism prevents this possibility. High mark up policy permits the leader to invest massively (compared to competitors) in new manufacturing equipment and in R&D dedicated to the next generation, (van de Gevel, 1996 and figure 4).

Intel's strategy, for instance, is to maintain its leadership by imposing a high priced new product[32], withdrawing it after other firms follow at lower price and using its high profit to invest in the next generation. When its leadership is lost, Intel tends to exit the market as in DRAM. As a result, the average product life cycle dropped from five years in the seventies to less than two years in 1989 and three months in 1997 (Linden et al. 20001). This strategy allows a decrease the volatility of profitability. Figure 4 shows the impact of changes of PC markets[33] on Intel and on Micron. Micron Technologies is specialised in DRAM subject to high volatility. Conversely, Intel is quite immune thanks to its high-end strategy and despite the reducing share of semiconductors' value in PCs.

Texas Instruments used to follow a complementary strategy: T.I tends to use its manufacturing capacities and a cost-effective strategy to enter rapidly. Then it cuts competitors' price and gain market shares enjoying scale economies. The inconvenient of this strategy is a persistence lower profitability and thus an incapacity to catch up in technological capabilities. In spite of its efforts, T.I has never been able to approach Intel's MPU performances[34]. Texas Instruments has moved to a leadership strategy by entering taking the lead of the DSP market (48% market shares in 1999). Its gross margin has doubled in three years and are immediately reinvested in dedicated capital and R&D investments.

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[31] IBM mini-computers or PCs based on a RISC architecture failed to enter the market.

[32] Intel's gross margin was 52% in 1995, 56% in 1996, 60% in 1999 and 62% in 2000. AMD has a gross margin closed to 35-40%.

[33] The average selling price of PCs has dropped from $2,000 in 1996 to $1,500 in 2000. Meanwhile, the breakdown of chips in PCs by value is nearly 50% for the microprocessor, about one-third for memory (Dataquest data reported by Linden et al. 2001).

[34] This was true despite a very early entry in the computer industry with the famous TI 99 4A.

Finally second source producers such as AMD tend to enter late and cut prices of mature products. This is a low investment strategy that may prove risky because it enables those players to gain enough experience to become independent.

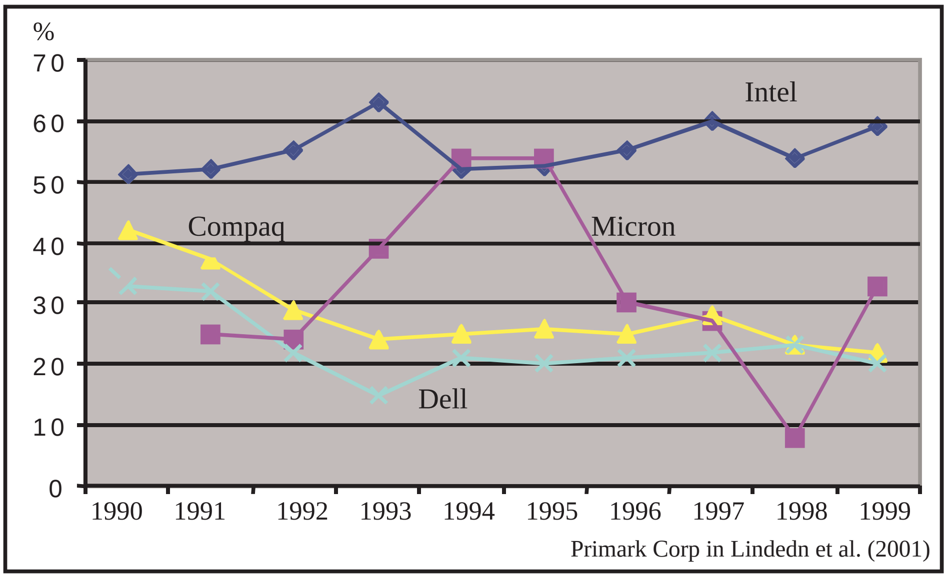

Figure 4: Gross Profit Rates in the PC World, 1990-1999

More generally, two sustainable strategies can be noticed:

- The leader has interest in investing in a given market to insure technological leadership. Product innovation aims at dominating a given application market by imposing a new standard and by increasing the product portfolio dedicated to several sub-markets. The expected return on R&D and capital investment is higher than its competitors because of reputation effects and of their experience in specific knowledge in design. As explained earlier, while spillovers on knowledge base are high across the industry, specific knowledge is firm dependent and even sometimes project dependent. It is mainly organisational and highly tacit knowledge. As a consequence, it is very difficult to imitate (cf. Iansiti, 1998).
- Followers or new entrants face different conditions. Their expectations on investments are lower and they necessarily lag in specific knowledge. But because there are scope economies in design, followers have an incentive to invest in higher hazard rate projects, that is in product innovation dedicated to nascent markets and/or complex projects, whereby innovation is highly uncertain. In case of success, they will become the leaders in the targeted application. Several examples illustrate this strategy. The more successful one is probably Texas Instruments with DSPs dedicated to telecommunication solutions, but also small companies such as ARM limited with Micrcontrollers for mobile phone solutions and set to boxes and MIPS with Micrcontrollers deidcated to set top boxes that have succeeded in imposing their products as standards in a specific market. Virtually all mobile handsets have a MCU, which design has been// licensed by ARM.

- Eventually, those new solutions may have consequences on several markets. Again because of scope economies in design, it may happen that a new product develops is based on a design solution that reveals valuable for other products and then happen to replace them however their reputation. This makes the previous specific knowledge obsolete and prevents any knowledge accumulation process and thereby possible shakeout pattern of evolution. This is even more relevant in ASICs' markets.

While all products have the vocation to become standard products, ASICs (Application Specific Products) are devices designed and produced for one customer[35]. When an ASIC solution is sold to several customers, it is considered as an ASSP (Application Specific Standard Product). ASICs are typically high tech complex products or systems (Hobday, 1998). New projects face strong technological uncertainty and encounter a high level of failure[36]. They are again more design intensive than logic chips and their development entails a very high level of uncertainty both in terms of resources and time needed to achieve the required specifications. ASICs have been the driver for IC industry's advances in all aspects of the value chain from flexible manufacturing, design technologies and tools to customer design support/service (ICE).

But currently innovation mainly occurs in design and in integration technology. ASICs require great competencies in system integration because they are essentially dedicated to new markets.[37] Whose constraints (portability, size, low power consumption, combination of analogue and digital processing, functional diversity, time-to-market, cost, etc.) impose a high level of hardware and software integration and a reduction of the number of ICs. As a consequence, IP and integration capabilities are the key distinctive elements. Moreover, ASICs provide a serious advantage to customers that do not necessarily have system integration capabilities and need ready made/turn key solutions. For instance, very few mobile handsets providers are able to design the base band system by themselves. In particular, late comers essentially use systems that are designed by component and IP suppliers.

In line with this evolution, System-on-a-chip (SoC) is becoming the standard design methodology to increase integration capacities (figure 5). SoC is an extension of ASIC technology. They are high-end, performance-oriented programmable systems (embedded systems). In theory, designers use large blocks of pre-designed cores like microprocessors, DSPs, SRAM, DRAM, etc. with a high rate of IP, and integrate them in a single chip. In reality, because of increasing constraints, cores tend to be completely re-designed in order to be perfectly adapted to the system's architecture. Further, IP is very rarely off-shelves IP but need to be adapted, and dedicated software tools (debuggers,…) are often developed in co-operation with the IP providers.

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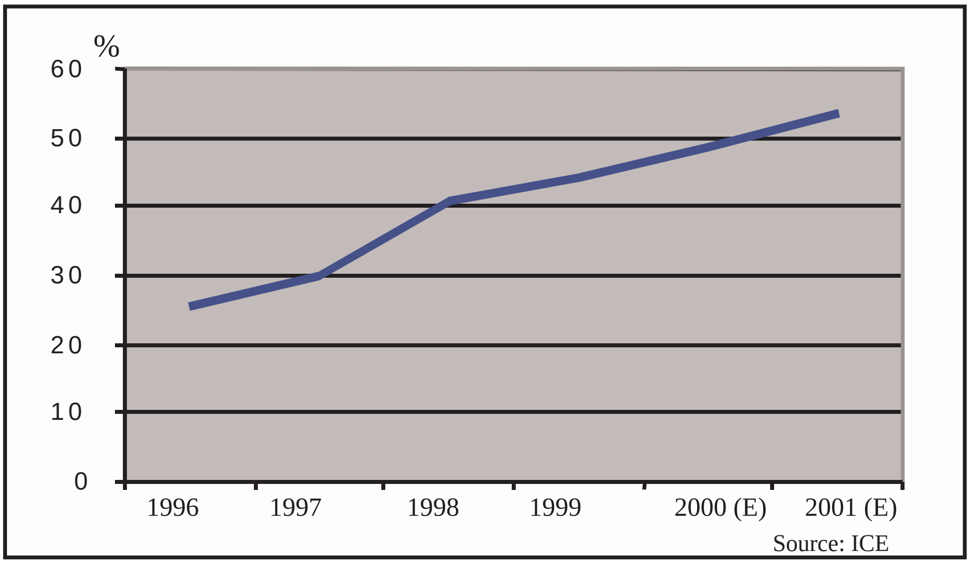
[35] ASICs can be split in three families, full custom ASICs (customer specific), semi-custom ASICs (standard ASIC dedicated to a specific need) and ASSP (standard ASIC dedicated to a specific application)

[36] Wawrzyniack (1999) reports that 25% of design starts fail to reach production due to complexity, product cancellation etc. All our case studies showed that even success would mean delays and over costs in resources essentially due to complexity and knowledge obsolescence.

[37] Modems, mass storage, cellular telephones and Personal Communications Systems (PCSs), networking switches and routers, voice over the Internet Protocol (VoIP), television set top boxes, short-distance wireless phones, camcorders, digital video disks (DVDs), Internet phones, other Internet appliances, and imaging etc.



Source: ICE

Figure 5: Evolution of SoC shares in Total ASIC

These characteristics justify two dynamics. On the one hand the advantage of companies horizontally diversified that can avoid transactions costs on IP (negotiate agreements, pay royalties and conflicts induced by contracts' incompleteness). This explains the relative leadership of companies such as IBM, or LSI logics that can develop all complementary competencies in house. On the other hand, integration can be a handicap because complementarities may not be known *ex ante* and flexibility is useful. In other words, mobilising only in house competencies limits innovative capacities. Consequently, the organisation of the industry evolves towards a set of networks of partners with complementary competencies (Vanhaverbeke and Duyster, 1997), each of them specialising in a particular module and/or in a particular position in the value chain (cf. Annex 1) as specialised innovation systems. Combined with very low barriers to entry (low sunk costs, low learning effects, competitive design trajectories and several potential applications) this promotes the arrival very innovative and very profitable small specialists.

Overall, the ASIC market in 1999 was dominated by big incumbent firms such as IBM (11%), Lucent (10.9%), NEC (10.5%), LSI Logic (9.3)% and Fujitsu (7.2%)[38]. This means that the five leaders do not share more than 48 % of the market. The HHI in 1999 was 0.05 only (approximately the same as in 1994 and twice lower than in 1991) with a high level of turbulence (5 entries and 8 exits in 1999 out of 59 actors[39]) that characterises a industry in its infancy stage…

Discussion

The life cycle model describes a general pattern of industries' evolution. It predicts that over time players' profit margins decline, entries cease and shakeout occurs. Then

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[38] Source: Dataquest

[39] 39 actors had less than 1% market shares

concentration increases towards an oligopoly. Conversely, in the semiconductor industry profit margins do not decrease over time, entries are increasing and shakeout does not occur. Finally, in the global market, the level of concentration does not raise sharply over time (Intel, has increased its market shares to 15.8% but all other top ten players have seen their market shares stabilise or even decline).

The case presented above showed that unlike the main assumption made by industry life cycle theories, knowledge dynamics does not necessarily follows a cycle from obsolescence to accumulation (or from competence destroying innovation to competence enhancing inovation). The semiconductor industry has experienced a persistent complementarity between process innovation and product innovation. Further, it seems that in design, the rate of knowledge obsolescence tends to decrease over time because of the development of new design solutions dedicated to new markets.

Finally, Whilst, the different sub-markets studied show very different structural conditions and different firms' conduct, there seem to be a rationale in firms' behavioural evolution. Vertically integrated firms tend to enter by building their competitive advantage on process competencies in order to play a consistent role in manufacturing. This enables them to enter the DRAM market, which is a commodity and very volatile market. They usually catch up by buying licenses to incumbents that use them as second source. Barriers to entry are high but new waves of entries recurrently occur because they can spend more than competitors on capital and equipment. They consequently can very rapidly produce state-of-the-art products. In other words, learning effects and insure successful entrants to survive and eventually move to more design intensive products and become more profitable.

Incumbent leaders in turn tend to move towards design intensive products such as microprocessors, microcontrollers and ASICs. They systematically move by diversifying from their knowledge base and building new specific knowledge in high opportunities markets. Enjoying both learning effects and lock in effects in those products (Gruber, 2000), they can impose a high mark up policy and insure their first mover strategy by investing more than competitors in the next generation. They are insured to enjoy a high rate of return on assets, as compared to lower and highly variable returns that follower earn. Consequently, they have no incentive to invest in new design trajectories (for new applications) whereby investments' risks of would be higher and profitability would not be guarantied.

Incumbent followers fight on price, which prevents them from catching up and reduce their relative profitability (compared with the leader). Thus, they have an incentive to invest in new project and build a specific knowledge (with its own design trajectory). In case of success, they take the lead as a first mover and enjoy a first mover advantage. On the global market leadership depends on the success of the applications whereby products are embedded.

Finally, a last class of entrants have been playing an important role for a decade or so. Fabless companies have no process knowledge. Their knowledge base is rather dedicated to applications' market and they are able to build specific knowledge in design based on high system integration capabilities. They usually have expertise in customers' needs. Their entry was made possible thanks to the increasing vertical specialisation resulting both from the development of IP markets and from the increasing number of flexible manufacturers (those new comers that aim to acquire the knowledge base in process technology). This results in contrasted dynamics in different sub-markets.

Does it mean that the life cycle is wrong? It is clear that, as already mentioned elsewhere (Klepper, 1997, Bonaccorsi and Giuri, 2000), the model is unable to account for all industry dynamics. Rather the purpose of this strudy was to suggest to make the model more general by taking into account several observations.

- Products and technologies must be distinguished. They have their own trajectory and do not necessarily rely on the same knowledge. While in DRAM product and technology had the same pattern of evolution, Logic chips and even more obviously ASICs have a completely different shape of evolution.
- It has been recurrently noticed that the evolution of market structure depends on dimensions that cannot be observed such as the evolution of customer tastes or the emergence of new technologies (Budd et al., 1993, Sutton, 1998, Gruber, 2000). However, I have shown that knowledge dynamics could be apprehended distinguishing fundamental from specific knowledge. Fundamental knowledge tends to be a-contextual and easily imitated whereas specific knowledge is application specific and even firm specific. As a consequence, there are two types of competition: first on knowledge base characteristics (usually cost driven) and on specific knowledge (quality driven).
- Specific knowledge may experience a sustainable high rate of obsolescence. This can be endogenously determined by taking into account strategic incentives structure of players. If new applications (requiring specific designs) recurrently emerge, or if fundamental knowledge provides several competitive technological trajectories, there are sustainable incentives for firms to invest heavily in new design trajectories. Because products relying on different designs are potential substitute (different product can be used in one application) knowledge obsolescence is high. In Sutton's words, homogeneity can be persistently low (various trajectories) and R&D spending may remain "effective." This results in a sustainable high rate of knowledge obsolescence and prevents the industry from experiencing shakeout.[40]

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[40] Note that Sutton, however, assumes that when trajectories proliferate, products are not substitute. This can be explained because if products are substitues, there should be a "trajectory shakeout". However, as explained above, substitution can be revealed *ex post*, that is affter a new product is developed. Then, if ex ante, firms are unaware of this potential ex post substitution they will try to develop a specific trajectory for the application. In the case studied, it is rather because products are imperfect substitute (such as RISC and CISC architectures in a first step. When two designs become pure substitute, then there is a "trajectory shakeout" but that can be compensated by the emergence of new trajectories dedicated to target new applications.

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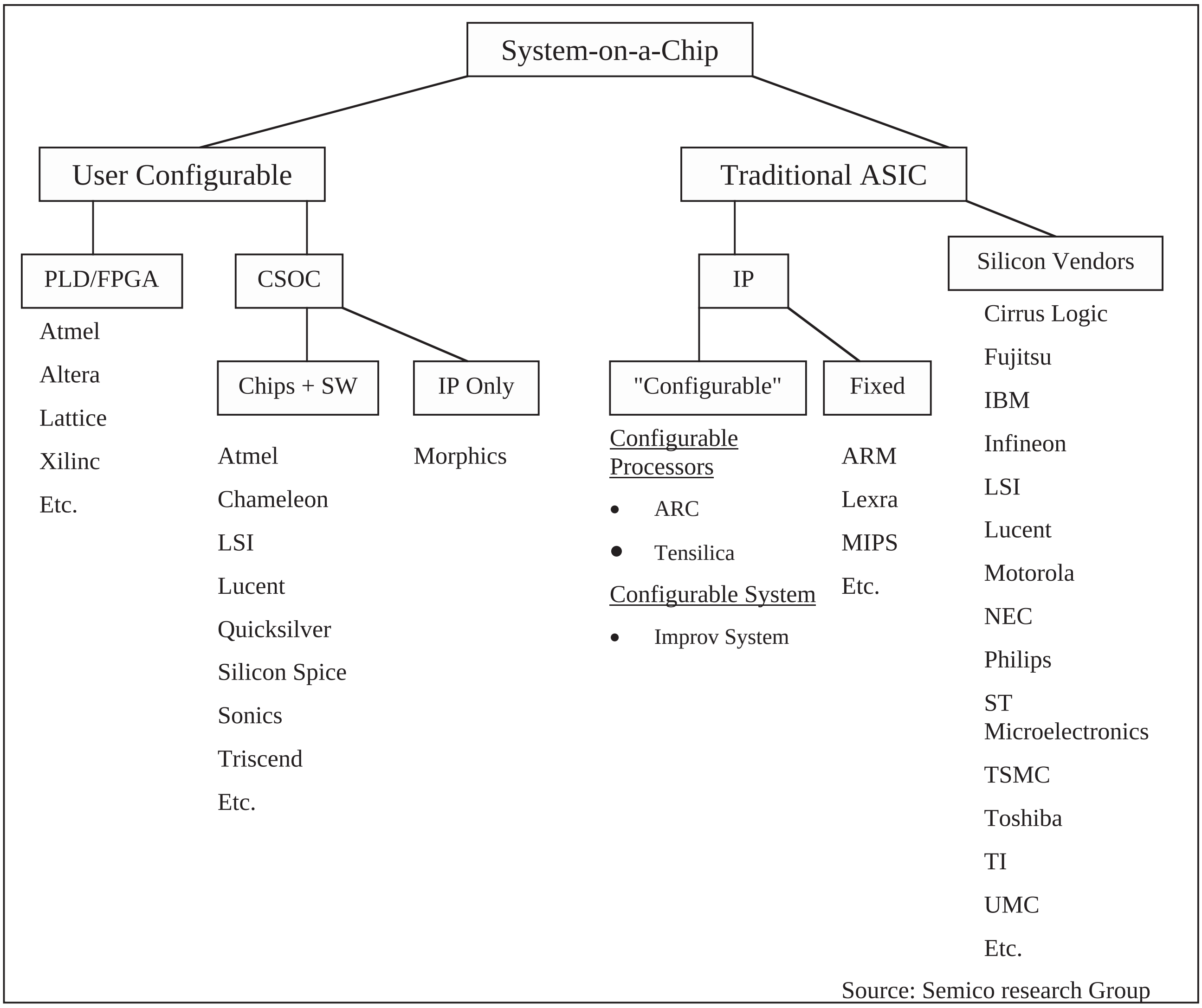
Annex 1: Sales of Semiconductors by Final Product Market, 1988-89



Source: Semico research Group