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Vertical Integration and Dis-integration of Computer Firms: A History Friendly Model of the Co-evolution of the Computer and Semiconductor Industries

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ABSTRACT

In this paper we present a history-friendly model of the changing vertical scope of computer firms during the evolution of the computer and semiconductor industries. The model is "history friendly", in that it attempts at replicating some basic, stylized qualitative features of the evolution of vertical integration on the basis of the causal mechanisms and processes which we believe can explain the history. The specific question addressed in the model is set in the context of dynamic and uncertain technological and market environments, characterized by periods of technological revolutions punctuating periods of relative technological stability and smooth technical progress. The model illustrates how the patterns of vertical integration and specialization in the computer industry change as a function of the evolving levels and distribution of firms' capabilities over time and how they depend on the co-evolution of the upstream and downstream sectors. Specific conditions in each of these markets – the size of the external market, the magnitude of the technological discontinuities, the lock-in effects in demand – exert critical effects and feedbacks on market structure and on the vertical scope of firms as time goes by.

1. Introduction

The history of the computer industry contains periods when at least the large computer firms were vertically integrated, designing and producing their basic electronic components, and periods where even the large computer firms bought those components from specialized suppliers. Over all but the earliest part of this history, the key electronic components have been semiconductors. To a large extent the remarkable increases in computational power and reductions in the costs of computation that have been achieved over this history have been made possible by advances in semiconductor technology, which on at least two occasions has been marked by the development of radically new kinds of semiconductor devices. This paper explores how the pattern of advance of semiconductor technology, and the demands for semiconductors, have influenced the structure of the computer industry, and in particular the extent to which large computer firms have been vertically integrated or not. The tool of exploration is a "history friendly" model.

In the following section we describe the patterns, particularly the dynamic patterns of vertical integration and disintegration of large computer firms, that we are interested in explaining. Then we consider various theories of vertical integration, and lay out the theory that seems most plausible to us. As we explain next, history friendly modeling is a method for exploring the logic of a qualitative theory and its adequacy to explain the phenomena it purports to explain. This discussion sets up our presentation of the model, and its runs. We pull strands together in our concluding section.

2. The Historical Phenomena to be Explained

In this paper, we can only briefly illustrate the history of the changing vertical boundaries of computer firms in terms of their vertical integration into semiconductors between the early 1950s and the mid 1980s. For a full discussion of these issues, see for example Langlois and Robertson (1996), Malerba (1985), Krickx (1995), Bresnahan and Malerba (1999), Langlois and Steinmueller (1999), Bresnahan and Greenstein (1999). The history of vertical integration and dis-integration of computer firms summarized here refers to the American case, because the technological and markets leaders in the industry were American firms.   Therefore we will not focus on Europe or Japan, which present interesting but different types of dynamics. Before we tell the story, it is necessary to make three remarks. First, we consider vertical integration and specialization by computer firms along a period of thirty years which was quite turbulent in terms of markets and technologies. The computer industry saw the introduction of mainframes first (1950s), followed by minicomputer (1960s) and finally by personal computers (1970s). In the semiconductor industry transistors were the main products during the 1950s, integrated circuits were introduced in the 1960s and microprocessor were launched in the 1970s. Second, we will focus on the development and production of standard semiconductor components. While large computer firms have always produced some types of custom components in-house, this has not been the case for standard semiconductor components: in specific stages of the evolution of the computer industry, standard semiconductor components have been produced in-house by computer firms, while in other periods they have been purchased on the market by specialized producers. Third, to keep the analysis simple, in this paper we will not discuss second sourcing or intermediate organizational forms such as networks and partial integration. [1]

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[1] In the history of the industry these forms have been used extensively for various reasons. First, in order to be secure of

At the very beginning of the industry, computer firms produced *mainframes* and were not vertically integrated. The first computer producers – IBM, Burroughs, Univac Rand, NCR, Control Data, GE and RCA - mainly purchased receiving tubes components (the electronic components that preceded transistors) from the open market. After the introduction of *transistors* (early 1950s) some of the largest firms such as IBM, RCA and GE became partially or totally vertically integrated into transistors. Conversely, the smaller mainframe firms purchased semiconductor components on the market. [2]   In the computer industry, IBM began to pull ahead in mid-1950s and it came to dominate the world market for accounting machines with the introduction of the 1401 in 1960, due to its three pronged investments in R-D, production and marketing.

The pattern of vertical integration by the leading mainframe firm - IBM- was reinforced when a new technological discontinuity - *integrated circuits* - took place in the early 1960s. IBM vertically integrated into integrated circuits development and production (first with hybrid integrated circuit technology (SLT) and then with monolithic devices). Three main reasons explain this pattern. First, integrated circuits embedded system elements and thus required close co-ordination between the system and the component producer in the design and development of both components and systems. Second, semiconductor designs became more and more "strategic" for system development, and therefore their design, development and production was kept in-house for fears of leakage of strategic information. Third, the rapid growth of the mainframe market and later on of the minicomputer market (1960s and 1970s) generated fears of shortages of various key semiconductor components among some of the largest computer producers. As a vertically integrated company, in the early 1960s IBM launched a new mainframe product: the system 360. Compatible System 360 lines allowed IBM to exploit economies of scale and scope. The System 360 led IBM to maintain the dominance of the world computer market during the 1960s. [3]

A major change in the patterns of vertical integration of the leading computer producer took place in the 1970s after the introduction of radically new semiconductor components – *microprocessors* - which opened a new fast expanding computer market – *personal computers*-. The major computer leader IBM dis-integrated from the production of microprocessors, because IBM confronted a major semiconductor industry leader – Intel – which emerged in this new quickly developing component market.   Intel and the other microprocessor firms could innovate and grow rapidly because they benefited from a very large and increasing demand coming not only from computers, but also form other final markets - such as telecommunications, consumer electronics, automobile, and so on –.   Dis-integration by IBM was accompanied by an increase in concentration in the semiconductor industry due to the leadership of Intel.

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the supply of semiconductors in case of large internal demand of components, the major computer producers often asked their semiconductor suppliers to license out their semiconductors so that they could benefit from a sure second source. Second, in order not to run the risk of overcapacity in their in-house production of components and to check for the quality of their in-house production, vertically integrated producers often only partially integrated into semiconductor production, producing a fixed amount of semiconductors internally and buying the rest from the market. Finally, various forms of networking in terms of cooperation in the development and of joint production of semiconductors have taken place during the history of the industry.

[2] Transistor technology improved greatly during the 1950s, and was sold to both computer producers as well as the military and other markets. Developments in transistors enabled significant improvements in mainframe performance, and some reduction in costs.

[3] Integrated circuits opened the possibility of designing computers - minicomputers - that had a considerable amount of power, could be produced at a much lower costs than mainframes and could be directed to a different market: medium size firms and laboratories.   In the semiconductor industry, demand coming from computer producers, other markets as well as the American military and NASA was satisfied in large part by new merchant specialized producers.

Also the new firms that had entered the personal computer market since the second half of the 1970s - Computer, Radio Shack and Commodore first, and a stream of new start ups later – were all specialized computer firms. These firms preferred to buy advanced semiconductor devices from large capable and innovative microprocessor firms, rather than try to vertically integrate. Thus Intel became the de-facto leader for the microprocessor market.

An episode that confirms the dynamics of integration and specialization that we have just recounted regards the entry by IBM into personal computers. When in the early 1980s IBM decided to enter the personal computer market, it did that as a non-integrated producer, buying its own semiconductor components - as well as peripherals and software - from outside suppliers. Also in this case, this decision was taken because IBM faced already quite capable producers of standard semiconductor components, it needed to speed up personal computer production and it did not have advanced internal capabilities in this respect.   The decision to develop personal computers jointly with a leading semiconductor component producer (Intel) - as well as with a software producer (Microsoft) - led IBM to a successful entry, but not to the domination of the personal computer industry (Bresnahan and Greenstein, 1999).

3 . *Theorizing About Vertical Integration*

What kind of theory is able to explain the patterns of vertical integration and specialization of computer firms presented in the previous section? The currently leading theories of vertical integration and specialization are mainly based on some version of the transaction costs approach. They focus their attention on the market failures that may emerge in the exchange of goods and services under particular conditions and propose the view that hierarchical coordination is to be considered as a substitute for market transactions in those cases. [4] The analysis of these issues may be framed in different theoretical settings: for instance, either bounded rationality (as in Williamson, 1975) or full rationality (as in contract theory) may be assumed. The language of strategic interactions is increasingly used in this context. Choices about integration – and the relative efficiency of markets vs. hierarchies – are viewed as determined by a calculation that weighs incentives advantages of markets against the governance advantages of hierarchical organization.

Without denying the clear relevance of transaction costs, we simply note here that this approach has a distinct static flavor and – quite obviously – considers transactions as the main unit and exchange as the primary object of analysis. Technologies, the properties of the goods and the characteristics of the agents are taken as given and the processes of vertical integration/ specialization are commonly examined as a choice at a given moment of time. In this paper, on the contrary, capabilities and technology are at the base of our appreciative explanation of vertical integration and specialization. This is done in a dynamic, evolutionary setting. Following Nelson and Winter (1982) and the capability-based view of the firm (Teece and Pisano 1994, Teece, Rumelt, Dosi and Winter, 1994), we suggest that a central factor explaining the vertical scope of firms is the process of accumulation of capabilities at the firm and industry levels. Capabilities are accumulated over time by firms through a variety of learning processes in specific technological, productive and market domains (Teece and Pisano, 1994). Such competencies tend to be typically sticky, local ad specific. Heterogeneity across firms is therefore likely to be a permanent feature of industries and the actual distribution of capabilities across firms in upstream and downstream industries is likely to

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[4] As it is well known, transaction costs are likely to be present in cases of asset specificity, asymmetric information and unclear definition of property rights. Under these conditions, limitations on effective writing and/or enforcement of contracts leave room for opportunistic behaviour, often leading to sub-optimal solutions.

bear a fundamental influence on the vertical structure of firms. For example the decision to specialize is elicited and critically depends on the actual existence of upstream suppliers at least as competent as the integrated firm itself.

In this framework, when products are systems with various components and subsystems, the ability to coordinate and integrate the design of such systems and components may constitute an important competence in its own right and a significant source of competitive advantage (Langlois and Robertson, 1995). Such advantage can be (more than) offset by considerations related to the risk of getting stuck in inferior technological trajectories, especially at times of rapid and uncertain technological change, or when suppliers are able to offer significantly superior products.

However, decisions to specialize and to vertically integrate are not entirely symmetrical. A firm contemplating the option of resorting to external sources for the supply of particular components can directly evaluate the relative quality of its internally produced product as compared to that available from the external supplier. In the opposite case, such a comparison cannot be so direct and it involves expectations on the ability to design and produce in-house. Moreover, if a firm decides to discontinue the development and production of certain components, it might find it difficult to resume such activities later on and in any case time and efforts are required. Thus, these decisions are not entirely flexible as time goes by.

In addition, the vertical scope of firms is to be analyzed not simply by considering the capabilities of a firm in isolation, but in its relationships with the other participants in the relevant industries (Jacobides and Winter 2005). For example, the degree of heterogeneity and the distribution of capabilities are crucially shaped by the processes of market selection, which tends to promote the growth of more efficient firms and of the related organizational arrangements and to penalize the laggards. Thus, market selection amplifies the impact of differentiated capabilities on the vertical scope of firms. If specialized firms have superior capabilities, selection will push for greater specialization; and vice-versa. Or, for instance, the growth of a competent supplier (or of a vibrant industry) is likely to induce processes of specialization of the system firms, as the supplier becomes able to offer increasingly better products. In turn, the process and the *loci* of capability development feed back on the conditions determining the entry of new firms. Thus, vertical integration or dis-integration can bear profound effects on the patterns of competition within an industry, creating the conditions for the entry and growth of new competitors exploiting capabilities developed in different contexts. [5]

In sum, a key point of this paper is that vertical integration and specialization are shaped by the co-evolution of capabilities, the size of markets and the structure of industries. The growth and dynamics of competencies in each one of two vertically related industries influence the evolution of the other sector and shape vertical integration and specialization (Langlois and Robertson, 1995, Jacobides and Winter, 2005).

The previous discussion identifies *capabilities* as a central factor affecting the vertical boundaries of computer firms. In particular, in this paper capabilities refer to the accumulation of firms' competences in specific technological and market realms and to the coordination and integration capabilities of components and systems in the development and production of new final products. Within this framework, a set of variables affect the level, type and accumulation of capabilities in various ways. In particular we will concentrate on four of them:

a)   *The size of firms.* Firm size affects the amount of R&D effort and thus the accumulation

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[5] Causation runs in the other direction, too: the process of capability development depends very much on the vertical scope of an industry. Let's take components development and production. Specialized firms that compete with other specialized firms accumulate knowledge and capabilities differently from vertically integrated firms.

of competences (and consequently the quality of systems and components produced).   In addition, size affects vertical integration because very large system firms may need a secure supply of components.

b) *The size of the market.* A large market allows for the entry of new specialized firms and for the growth of capable companies. This is a very Smithian reasoning placed into a capability perspective.

c) *The market structures of two vertically related industries.* The above discussion about the need to consider the distribution of capabilities among industry participants may be linked to structure of industry: for example, a monopolistic system industry tends to become   vertically integrated into components when confronted with a fragmented upstream industry composed by small firms. On the contrary, a fragmented system industry tends to specialize when confronted with a monopolistic component industry .

d) *Major technological discontinuities* and the related *competence destruction.* Major discontinuities change the knowledge base and the type of demand and lead to the entry and growth of firms with totally new competences. Under these conditions, established vertically integrated firms face pressures towards dis-integration;

The discussion developed above and the variables that have been identified allow us to recast and explain the dynamics of vertical integration by computer firms presented in the history in section 2.   At the beginning of the computer industry, *mainframe* firms started specialized and over time a company gained the leadership and an almost monopolistic position in the system industry. This company vertically integrated, as it was large, needed security of supply of components and once integrated, its large profits in systems led to rapid technological advance in its components. Conversely, for the independent *transistor* producers the extent of the external market was not so big to spur an increase in their size comparable to that experienced by the system producers. A dominant component company did not emerge and vertical integration of system firms further reduced the opportunities of growth for component companies.

When *integrated circuits* were introduced, the vertically integrated *mainframe* producer faced pressures towards vertical dis-integration since the new component firms were able to produce better products. However, since the external market for the new types of components was still not large enough, specialized component producers remained relatively small (compared to the largest system producer) and did not have massive resources for R&D and innovation. After an initial period of strong technological turbulence, when the new technology started to mature, the system company vertically integrated into integrated circuits: vertical integration allowed close coordination between components and systems, components have become more strategic for system development and production and security of supply reasons became stringent.

Dis-integration of the leading mainframe producers took place instead when a third technological discontinuity – *microprocessors* - took place. This time the vertically integrated mainframe producer faced a new cohort of component producers that could benefit from the sharp technological discontinuity and thus supply vastly superior products compared to integrated circuits, so that catching up in components by an established vertically integrated mainframe producers was slower. Moreover a much larger external market - not dependent only from mainframe producers – allowed these new semiconductor firms to invest much more in R&D, grow quickly and achieve high levels of components quality. In this process, a leading component company emerged and dominated the industry. Specialization characterized also the new *personal computer* producers, because these firms remained relatively small as compared to the leading microprocessor company, which supplied the computer industry as well as other large external markets.

4. The logic of history-friendly models

We believe that the differential development of capabilities for designing and producing semiconductors among firms, the causal driving factor we highlighted in Section 3, has been the principal force behind the pattern of vertical integration and disintegration of computer firms described in Section 2. But how to "test" that theory, or at least demonstrate its plausibility? The vehicle used in this paper is the design and running of a "history friendly" model.

"History-friendly models" are intended to enhance understanding of particular interesting and important economic phenomena, in this case the swings in vertical integration and disintegration in the American computer industry. They are closely focused on these phenomena, as contrasted with being intended to illuminate broad and general issues, although what one can learn from a successful history friendly model may go well beyond the particular phenomena on which it is focused. History friendly models generally are simulation models, and this one is. The aim of history friendly modeling is not to explain, in the sense of closely matching through a simulation, the quantitative values observed in the historical episode under investigation, nor is the specification of the model parameters driven by the objective of getting as close as possible to actual empirical values of variables in the actual context being modeled. Rather, the objective is to explore whether particular mechanisms and forces built into the model can generate, and in that sense explain, the patterns in question.

The design of a history friendly model is guided by the theories, generally verbal, that informed observers and empirically oriented economists who have analyzed the phenomena have put forth as their causal explanations, and which the model builders find plausible as well as interesting. History friendly modelers, like ourselves, believe that much of productive economic theorizing is presented as explanations of particular empirical phenomena by those who know a lot about the empirical details. Much of the theorizing discussed in Section 3 is of this sort. However, we also believe that it is difficult, sometimes impossible, to check out the logic and the explanatory power of such verbal qualitative theorizing, without formalizing the argument. A history friendly model is built on a simplified formal representation of the theory being considered, and aims to test the consistency and power of that theory by exploring the performance of the model.

The history friendly model presented and tested here is focused on the factors affecting firm capabilities described in Section 3, and presumes that a central factor determining whether computer firms produce their own semiconductors or buy them from a supplier is where the strongest capabilities of semiconductor design and production are located. In being oriented this way, our model of the determinants of vertical integration or specialization places the emphasis differently than do the "transaction cost" theories that have been prominent in the industrial organization literature. The question then is: how well can such a model do in explaining the observed pattern?

5. The model

5.1 An Overview

The model we describe in this section is designed to capture, in highly stylized form, the key elements of the verbal explanation that we find most persuasive for the observed dynamics of vertical integration and, later, vertical disintegration in the American computer industry over the period between the early 1950s and the late 1980s. The dynamics of the model, as the verbal

account, is shaped by characteristics of the market for computers, the technologies determining computer performance, and exogenous developments in semiconductor technology, all of which led to changes over time in the incentives and capabilities computer firms had to integrate vertically. .

Firms in the computer industry compete for customers. At any time a computer produced by a particular company is characterized by two attributes that are relevant to its potential purchasers: performance, and cheapness (the inverse of price). Other things equal, the share of market sales gained by a particular computer is a function of the merit of its design in terms of these two attributes relative to the merit of other computers on the market, although sales are also influenced by brand loyalty and inertia of customers. In turn, both of these design attributes are determined by the way the computer is designed as a system, and the quality of the semiconductors that go into that system.

Both of these design factors tend to improve over time as a result of R&D done on systems, and on semiconductors. Systems R&D is done by computer produces. R&D on semiconductors is done by semiconductor firms, and also by computer firms that ha v e vertically integrated into the production of their own semiconductors.

Computer firms that sell more computers, on either market, are more profitable than firms that sell less. High profits induce and permit a firm to grow and as profitable firms expand their sales, they increase their R&D spending. Since on average higher R&D spending enables a firm to make larger improvements in the computers it sells, there is a strong potential in this model for a dominant firm to emerge through the dynamics of competition. Diminishing returns to R&D tend to damp this tendency, as does brand loyalty, at least in the short run.

The path of semiconductor technology plays a particularly important role in the model. In particular, it is assumed that there are three distinct eras. In the first, all semiconductors are discrete transistors. In the second era, integrated circuits emerge. In the third, microprocessors. Within each era, there is continuing improvement in the basic semiconductors being produced and sold, but the advent of a new type of semiconductor is associated with a speeding up of the rate of progress. Also, before the advent of microprocessors all computers are "mainframes". The development of microprocessors not only permits improvement in the design merit of mainframes, but also enables a different kind of computer to be designed and produced, PCs, which are significantly cheaper than mainframes although having less impressive performance. Mainframes appeal to customers who greatly value high performance; we will call these "big firms". PCs appeal to a different group of customers, "small users".

The advent of new types of semiconductors is marked by the entry of new specialized semiconductor firms, who compete with established producers and each other for sales. Semiconductor firms sell not only to computer firms, but to other users, and the emergence of integrated circuits and of microprocessors stimulates the development of these other markets as well as demand from computer manufacturers. The introduction of PCs and the opening of a new market for computers induces the entry of new computer firms specializing in PCs.

The central orientation of this model is towards factors that explain whether computer firms are specialized, buying on the market the semiconductors they employ in the computers they produce, or whether they are vertically integrated, designing and producing their own semiconductors. In the model, all computer firms are born specialized. But once in the computer business they can decide to integrate and design and produce their own semiconductors. And if integrated, they can decide to get rid of their semiconductor design and production unit, and go to the market again for their components.

The decision to be integrated or not partly rests on the advantages of being able to design both the components and the system together, which can be considerable. It also partly rests on judgments as to the importance of being able to control the supply of one's inputs, and on whether the firm believes it can produce semiconductors as or more efficiently than specialized suppliers.

In general, large semiconductor firms are more likely than small ones to believe they can efficiently design and produce their own semiconductors. This tendency to integrate vertically is enhanced if the industry producing semiconductors for sale is fragmented, and there is considerable experience with the kind of semiconductors in use. On the other hand, vertical integration is deterred if there is a large competent semiconductor supplier who spends a lot on R&D, or when a new kind of semiconductor is just emerging and the best ways to design and produce them is highly uncertain. In the former case, even a large computer firm may doubt that it can produce semiconductors as efficiently as the dominant specialized supplier. Whether or not large semiconductor suppliers come into existence is a function of the size of the market for semiconductors outside of computers, as well as the portion of the computer industry that purchases rather than makes the semiconductors it uses.

This is the model in broad outline. In the remainder of this section we describe some of the important details.

5.2 *Computers*

At the beginning of the simulation, firms (numbering 12 in the current parameter setting) start producing and selling computers. A computer is characterized by two characteristics: its performance, and its cheapness (the inverse of its price). As noted, available component technology initially permits only the production of mainframes. Later, the advent of microprocessor technology enables the development of PCs. PCs have less performance than mainframes, but are cheaper. The two different kinds of computers appeal to two different kinds of customers.

As a consequence of firms' R&D investment, and the advance of component technology, the characteristics of computers of a given type improve over time. The advance ot mainframes is along a ray mapping out the performance– cheapness characteristics of that kind of computer. The advance of PCs also is along a ray, characterized by a higher ratio of cheapness to performance than the mainframe ray. The distance out along the ray associated with its particular computer type defines the "merit of design" (M, or "Mod") of a particular computer. To keep the notation simple, in what follows we do not explicitly denote whether the M refers to a mainframe or a PC computer. The context will make that distinction obvious.

In turn, computers are produced by combining two main inputs, systems (s) and components (c).[6] The level of the merit of design, M, is given by a CES function:

$$M_{i,t} = A \cdot \left[\tau \left(M_{i,t}^{C} \right)^{-\rho} + (1 - \tau) \left(M_{i,t}^{S} \right)^{-\rho} \right]^{\left(-\frac{1}{\rho} \right)} \qquad (1)$$

with A > 1, $0 < \tau < 1$ and $\rho > -1$. The elasticity of substitution is: $\delta = 1/ (1 + \rho)$. In the CES functions the weight attributed to the Mod of components (τ) is always higher than the weight on the Mod of systems. PCs have a comparatively higher weight on components as compared to MF (i.e. $\tau_{PC} > \tau_{MF.}$) and the elasticity of substitution, δ, is higher in PCs than in MFs. Thus, improvements in components are reflected more powerfully in PCs than in MFs. [7]

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[6] Systems are always produced by computer firms and cannot be sold separately from computers.

[7] The trajectories followed by firms in the space of the characteristics are assumed to be fixed and equal among firms producing computers of a given type. Given the level of the merit of design for a computer and the slope of the MF and

.

Different computer types, either mainframes or PCs, are produced by different companies. We exclude the possibility of diversification in this model.

5.3 Demand for computers

Customers of computers are characterized by their preferences about the two attributes that define a computer design - performance (z) and cheapness (w). There are two buyer groups, one consisting of "big firms" and others who are especially interested in performance, and care less about cheapness, and the other of "small users" who are especially concerned about cheapness, and who value performance less than do big firms. "Big firms" buy mainframe computers. "Small users" buy PCs, when these become available after microprocessors come into existence.

Within each buyer group, there are many individual buyers.[8] While buyers are identical within each group in terms of the preferences that lead them to one type of computer, they differ in specific behavior because they have different histories, which are partly randomly determined in the model. Buyers respond to the computers offered by different firms according to the relative merit of their products, but also according to other considerations, including their specific buying history. Markets are represented as being characterized by frictions of various sorts, including imperfect information and sheer inertia in behavior, brand-loyalty (or lock in) effects as well as sensitivity to firms' marketing policies. These factors are captured in a compact form by the share of computer brands in the overall market for that type time t-1: the larger the share of the market that a product already holds, the greater the likelihood that a customer will consider that product. Finally, there is a stochastic element in buyers' choices between different computers.

We represent the market process by characterizing the probability distribution of buyer's choices among the different computers of the desired type. This probability is a re-normalized counterpart of a purchase propensity that depends on the merit and market share of a particular computer. Formally, the "propensity", L_{it} , for computer i to be sold to a buyer at time t is given by as:

$$L_{i,t} = M^{\alpha 1} (1 + s_{i,t-1})^{\beta 1} \tag{2}$$

where $s_{i,t-1}$ is the market share, $\beta 1$ is the exponent indicating the bandwagon effect on computer market. The probability $Pr_{i,t}$ of the computer i being sold to a buyer at time t is given by:

$$Pr_{i,t} = \frac{L_{i,t}}{\sum_i L_i} \tag{3}$$

In short, the demand for a computer depends positively on its Mod and on its market share in the previous period. The probability that a computer from a specific firm is purchased by a buyer is proportional to the "propensity," normalized to sum to one. Then for a computer firm, the total computers sold are equal to M_{it} times the number of buyers. If α1 = 1, a 1% increase in merit

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PC trajectories, the values of cheapness (*w*) and performance (*z*) that appear into the demand function are defined using the following trigonometric formulas:

$$w_{i,t} = \cos(\beta) \cdot M_{i,t}$$

$$z_{i,t} = \sin(\beta) \cdot M_{i,t}$$

where *β* indicates an angle expressed in radians, and is different between PC and MF.

[8] To avoid unnecessary computational burdens, we do not scale buyers to a realistic size relative to firms: the model assumptions simply capture the idea that buyers are small and numerous. Optionally, each "buyer" in the formal model could be interpreted as representing a number of consumers or small firms.

across all firms selling to a buyer group implies a 2% decrease in price/performance, which gives rise to a 1% increase in the number of computers sold. In this sense, the implied price elasticity of market demand for computers of constant quality is .5 α1.

5.4 The market for components

Components are bought by specialized producers of computers and also by customers in other markets (i.e., the external markets). As described above, there are three different component technologies, which become available at different times. In this version of the model, the transistor, integrated circuit and microprocessor technologies become available respectively at periods 1, 40 and 120. We interpret a "period" as a calendar quarter. At the beginning of the simulation and at the time of each technological discontinuity a new cohort of firms (12 in this version of the model) enters the market, producing components with the latest available technology.

The demand for components, faced by component firms, comes from two sources:

(i) Demand for components from users other than computer firms. The size of this external market is exogenous, parametrically determined, and firms gain probabilistically a fraction of it as a function of their merit of design and of their previous market share, as in the computer market. External demand plays a critical role in the model, since it allows component producers to survive and grow in the early stages of development of a new technology and to improve the merit of their components.

(ii) Demand for components from computer firms which have decided to outsource component production (specialized computer firms).

When a specialized computer firm seeks component supplies, it scans the market for potential suppliers. Competition among component producers is modeled in a fashion that parallels the competition of computer producers. A specialized computer producer contracts with a component producer according to a probability function that reflects the relative technical merit of the components offered by different suppliers: the higher the merit of a component, the higher the probability that its producer signs a contract with a computer producer. Moreover, like the demand for computers, the demand for components is influenced by bandwagon and lock-in effects captured by the previous market share.

Formally:

$$L_{i,t}^{C} = M_{c}^{\alpha 2}(1 + s_{i,t-1})^{\beta 2} \qquad (4)$$

and

$$\Pr_{i,t}^{C} = \frac{L_{i,t}^{C}}{\sum_{i} L_{i,t}^{C}} \qquad (5)$$

where M_{C} is the merit of design of the component, L_{it}^{C} is the propensity of component producer i to be selected, $s_{i,t-1}$ is the market share of firm i in the previous period and $\Pr_{i,t}^{C}$ is the probability of a supplier to be selected.

A component firm that signs a contract sells a number of components reflecting its customer's computer sales and the number of components required per computer; in the current simulations that parameter is set to one. After signing the contract the computer firm is tied to the component

supplier for a certain number of periods, which is a parameter of the model. When this period expires, a new supplier might be selected, using the same procedure, if the firm still decides to buy components on the open market.

The external market is conceptualized in the same way as the computer market, i.e., it comprises a number of heterogeneous buyer groups or submarkets to which component firms may sell. However, the submarkets of the external component market are not modeled explicitly. A firm simply gets a fraction of the total value of the external market equal to $\Pr_{i,t}^{C}$.

5.5 *Firms' behavior and technical progress*

At the beginning of a simulation, firms start with a given merit of design, they start to make operating profits and invest in R&D.

Operating profits, π, are calculated in each period t as:

$$\pi_{i,t} = q_{i,t} \cdot p_{i,t} - q_{i,t} \cdot o_{i,t} \tag{6}$$

where q_{it} is the number of computers sold, depending on the merit of design level and on the number of buyers attracted by the firm, p is the price and o is the production cost of a computer. Price is obtained by adding a mark-up, η , to costs:

$$p_{i,t} = o_{i,t} \cdot (1 + \eta) \tag{7}$$

Costs are in turn derived from the merit of design achieved by a computer, considering that the price of a computer must be equal to the inverse of the achieved cheapness.

The price of components charged by component suppliers is determined symmetrically by adding a fixed mark-up to unit production costs.

For specialized computer and component firms, R&D expenditures are calculated following a simple rule of thumb: a constant fraction of profits (100% in this version of the model) is invested in R&D in each period. By investing more in R&D, firms buy themselves higher probabilities to increase their merit of design. (The R&D spending of integrated computer producers is discussed below.)

Technical progress is modeled using the "draw scheme" used in Nelson and Winter (1982). There are two such draw schemes, one for the components and one for systems, which differ only as regards the means and variances of the normal distributions involved. Thus, integrated firms have two technical progress functions, while specialized computer firms and component firms have only one technical progress function, respectively for systems and for components. According to these schemes, in each period firms draw possible values of the natural logarithm of Mod from a normal distribution. The number of draws (d) that any one firm can take is set proportional to its R&D spending (R); the parameter of proportionality v is the cost of a draw:

$$d_{i,t} = \frac{R_{i,t}}{v} \tag{8}$$

When this calculation fails to return an integer value, a random choice is made between the adjacent integers values in such a manner as to make the expected number of draws equal to the

result of the calculation in (8). For example, a result of 2.75 translates into 3 draws with probability .75 and 2 draws with probability .25.

The distribution of potential new Mod values is more favorable when the current value is higher; in other words, technological change is partly cumulative at the firm level. The distribution also becomes more favorable with the passage of time, because it reflects the influence of "public knowledge" -- a variable exogenous to the industry and conceived as representing the level of knowledge available in published academic research, specialized journals, or techniques that have become widely known). The details of these assumptions follow.

Public knowledge is specific to each basic component technology. When a new technology is introduced, its corresponding level of public knowledge is lower than that reached by current technology, but then it grows faster and surpasses the public knowledge of the older technology. The rate of growth of public knowledge approaches an asymptotic value characteristic of the technology, with later technologies showing more rapid growth than earlier ones. An integrated computer firm is assumed to adopt the new technology — meaning that its R&D results subsequently reflect the public knowledge of the new technology -- when the mean of its own distribution for component draws becomes inferior to the level of the public knowledge of the new technology.

In each period, the values of the Mod obtained through the firms' draws are compared with the previous value of Mod, and the highest among these values is kept. Thus, more draws increase the likelihood to get a higher Mod for both systems and components. The result of an individual draw is determined initially as a value for the natural logarithm of the Mod value drawn from a normal distribution. The mean of this distribution is a weighted average of the logarithm of the Mod (ln(M)) at time t-1 of firm i and of the logarithm of the level of publicly available knowledge, K, at time t. The standard deviation of the distribution is a parameter σ. Exponentiating the result of the individual draw yields the value to be compared with the previous Mod (and other draw results, if any).

$$M_{i,t} = h \cdot \ln(M_{i,t-1}) + (1-h) \cdot \ln(K_t^k) \qquad\qquad (9)$$

where

$$K_t^k = l_K \cdot \left[e^{\varphi_k \cdot t} \cdot \left(1 - \frac{1}{n \cdot (t - tc_k)} \right) \right] \qquad t > tc_k \qquad (10)$$

where l and n are parameters and tc_k is the date of introduction of component technology k (k =TR,IC,MP). A higher value of l yields a higher track for the public knowledge trajectory, and a higher value of n means that the asymptotic growth rate φ_k is approached more quickly. With n set to a high value, which is typically the case in our simulations, a new technology appears and then improves rather abruptly to quickly surpass the prevailing one (in terms of public knowledge).

By setting the parameter h close to zero or one, the model is capable of representing extreme cases where progress is in the industry is, respectively, "science-based" or "cumulative". In the former case, firm R&D expenditures are not the ultimate drivers of progress, they essentially cover the cost of commercializing innovative possibilities created outside the industry. In the latter case, firms are creating the effective technology, in a step-by-step cumulative process. Since the cumulation is firm-specific, whereas public knowledge is a shared resource, it is clear that firm Mod values should be expected to diverge from each other to a greater extent when h is high than when it is low.

We now turn to a question that is central to the logic of vertical integration in the model, the determination of R&D expenditures for integrated computer firms. First, such firms make the same expenditures on systems R&D that a specialized computer firm of the same Mod would make; they spend their profits on systems R&D.

While the production costs of integrated computer firms producers are a function of their achieved merit levels, the production costs of specialized producers are instead determined as the costs of the system plus the cost of buying the components on the marketplace, i.e. the price charged by the particular supplier from which the computer company is buying. In the model, we assume that an integrated and a specialized firm having the same computer Mod have also the same production costs for a computer. For a given component Mod, the production cost of internally produced components is equal to the production cost of the externally produced components. The additional component costs attributable to the mark-up charged by component suppliers and which are "saved" by an integrated firm - are invested in component R&D by integrated producers and treated as a cost in the short run. The R&D, however, confers long-run benefits. If these R&D benefits are sufficiently large, the integrated form is favored and tends to persist by virtue of its higher Mod values.

The extent of the benefits depends on the extent to which integrated producers enjoy coordination advantages as compared to specialized producers, by virtue of the fact that they can produce components tailored to their systems – and, as a consequence, the productivity of their R&D efforts on components is enhanced. To represent this effect in the model, we assume that their component R&D expenditures are costlessly augmented by a certain factor, which we call *spillover (f)*. This factor is central to the economic advantages of integration vs. specialization.

In sum, component R&D - $R^C_{i,t}$ - of an integrated computer producer is:

$$R^C_{i,t} = \eta \cdot c^C_{i,t} + f \cdot R_{i,t} \tag{11}$$

where c^C is the cost of its component and $c^C * \eta$ is the difference between the price the component would command in the open market and its cost for the producer. Since specialized component firms are assumed to spend their operating profits on R&D, this formulation means that the integrated form is economically equivalent to the specialized form when the spillover, *f*, is equal to zero, but is in a superior overall cost position if *f* is positive. Thus, for any positive value of f, integration is the economically superior form of organization for R&D directed to incremental advances in a given technology – but the consequences of this for industry evolution are qualified by the fact that it is the specialized component firms that pioneer entirely new technologies.

Specialized computer producers invest all of their R&D on systems and obviously do not enjoy the coordination advantages. Component suppliers spend all their R&D on the development of components.

5.6 Vertical Integration and Specialization

Specialized computer producers may decide to vertically integrate into semiconductors, if they think that they can design and produce components that are comparable in merit to those offered by specialist suppliers. As noted previously, this is more likely to be the case if computer producers are large enough compared to extant suppliers, so that they can fund a larger flow of R&D expenditures. The decision to vertically integrate also depends probabilistically on the age of the component technology.

These considerations are reflected in the following formulation. The probability of integration for each computer firm is determined as follows. Let:

$$V_{i,t} = \min\left(\frac{A_{k,t}}{g};1\right)^{\vartheta 1} \cdot \left(\frac{q_{i,t}}{q_t^C}\right)^{\vartheta 2} \qquad (12)$$

where:

A_{kt} (k =TR,IC,MP) = t – (Starting time of Technology γ); $q_{i,t}$ is the number of computer sold by the computer producer; q_t^C is the number of components sold by the largest component producer and g is a parameter .

Then:

$$\Pr ob(Integrate)_{i,t} = \frac{b \cdot V_{i,t}}{1 + b \cdot V_{i,t}} \qquad (13)$$

where b is a parameter. This formulation corresponds to the assumption that the odds favoring integration (P/(1-P)) are proportional to V. Since V is not necessarily below one, it cannot directly serve as a probability.

The decision to specialize is not symmetrical to the decision to vertically integrate, because its information base is significantly different. It is modeled as depending on a comparison between the merit of design of the component produced internally and the merit of the best component available on the market.

Specifically, the probability of specialization for each firm is determined as follows: Let:

$$Z_{i,t} = \max\left(\frac{\max M_t^C - M_{i,t}^C}{M_{i,t}^C},0\right) \quad , \qquad (14)$$

where $max\ M^C$ is the higher component Mod available on the market. Then:

$$\Pr ob(Specialize)_{i,t} = \frac{a \cdot Z_{i,t}}{1 + a \cdot Z_{i,t}} \qquad (15)$$

This says that the odds favoring specialization are proportional to Z.

A specialized computer firm may also decide to change its supplier, if a better producer has emerged in the market. The procedure for changing supplier follows the same rule for the specialization process. That is to say, every n periods after the last decision to specialize or the last change of supplier, a specialized firm checks if a better supplier than the current one exists. If this is the case, a new supplier is chosen using the rating mechanism described in the discussion of the demand module.

5.7 Exit

Both computer firms and component suppliers exit the market when their market share falls under a certain minimum threshold.

Specifically, the exit rule is defined as follows. For each computer firm and in each period, the variable

$$E_{i,t} = (1-e) \cdot E_{i(t-1)} + e \cdot s_{i,t} \qquad\qquad (16)$$

is computed, where n is the number of firms active in the market at the beginning of the simulation, $s_{i,t}$ is the market share of firm i at time t and $0<e<1$ is a parameter. Then, if $E_{it} < E < 1/n$, where E is a constant threshold (equal to 0.05 in the current parameterization), the firm exits. Thus, for example, if $E = 1/(2n)$, the rule says that firms exit if they operate long enough at half or less of their initial market share.   A small value of e has the effect of allowing a lot of time for firms to recover from temporary competitive setbacks. (As is well known, equation (16) generates the E series as a geometric distributed lag function of the s series, with weights decreasing into the past like e^t .) E is initialized at 1/n.

The rule governing the exit of the component producers is different and simpler. The probability of exiting of any one firm is an increasing function of the number of consecutive periods in which it does not sell to a computer producer. So the rule is defined as follows:

$$W_{i,t} = \left(\frac{x_{i,t}}{100}\right)^2 \qquad\qquad (17)$$

where $x_{i,t}$ is the number of consecutive periods in which firm i does not sell to a computer producer. Then $W_{i,t}$ is compared with a number U drawn from a uniform distribution: if $W_{i,t}$ is bigger then U, the component firm exits the market.

6. The Simulation runs

6.1   The History-Friendly Simulation

The history-friendly simulation has been constructed by applying to the model a parameterization that reflects the basic assumptions about the processes which have driven industrial evolution, vertical integration and specialization according to the historical accounts and the interpretative framework discussed earlier. It is based on the following assumptions on the relevant variables and on the values of the parameters:
-    the size of the external market for components is relatively small in the case of transistors and integrated circuits and significantly higher for microprocessors;
-    the weight of components with respect to systems is higher in determining the merit of design of personal computers as compared to mainframes;
-    personal computers are cheaper than mainframes, so that a whole new class of customers, who attribute much more value to cheapness than to performance, buy the new type of computers and the personal computer market grows rapidly;
-    in computers demand lock-ins are very important for mainframes and much less so for personal computers;
-    in semiconductors demand lock-ins effects are much stronger in microprocessors as compared for transistors and integrated circuits;
-    the technological discontinuity related to microprocessors allows much higher improvements in component designs - and thus it is much sharper - than the previous one related to integrated circuits.

// FIGURE 1 ABOUT HERE //

Under this parametrization, the simulation replicates the key aspects of the story recounted above. In this as well as the following exercises, results refer to averages over 100 runs. Figure 1

reports the Herfindhal index and the integration ratio, which gives the number of integrated firms over the total number of firms in the industry.

In the first period the computer industry experiences a sharp increase in concentration. The rise of a monopolist in mainframes is sustained by significant "lock-in" effects on the demand side, which magnifies early technological advantages and protects the leader from competition. Because of its large size, the leader vertically integrates. Integration is sustained over time because the large profits of the monopolistic mainframe producer leads to massive R&D investments and therefore to rapid technological advances in its components. On the contrary, semiconductor producers cannot exploit large lock-in effects in demand and demand itself is relatively small. In fact external demand is not large and the computer firms that vertically integrated take away demand from the best and largest semiconductor producers, reducing concentration in the component industry.

At the time of the introduction of integrated circuits, new semiconductor companies enter the market and concentration diminishes. However, the dominant mainframe firm remains vertically integrated: This is because the technological discontinuity in semiconductors is not very high, the size of the external market for semiconductor is not large enough to sustain a significant growth of the new entrants and the mainframe producer continues to be very large as compared to the new semiconductor producers. Competition in the semiconductor market induces a sharp shakeout in semiconductors and concentration gradually begins to increase. When vertical integration is complete in the computer market, the semiconductor producers are left with no demand and exit this market. As a consequence, concentration falls to zero.

The third technological discontinuity sets in motion a different story. Microprocessors constitute a major technological advance as compared to integrated circuits and a large external market supports major R&D investments, the developments of high quality semiconductors and the grow in size of microprocessor firms. In addition, in microprocessors lock-in effects in the demand for components - both in the computer market and in the external market - are much more significant than in the earlier phases so that a microprocessor leader emerges. Thus technological catching-up in microprocessors by the integrated mainframe producer is quite difficult, and dis-integration takes place. This in turn generates a substantial new demand for microprocessors and fuels further advances in the merit of design of the components produced by the leading semiconductor company. In the personal computer market, most personal computer producers remain relatively small [9] as compared to the leading microprocessor supplier who has emerged before any of the new producers of personal computers can became very large. Moreover, in the case of personal computers lock-in effects on the demand side are limited (as compared to mainframes): hence, no personal computer producer can establish and maintain a dominant position becoming large enough to make vertical integration reasonable. As a result, personal computer firms remains specialized. The establishment of a monopoly in the supply of components contributes however to maintain competition in the personal computer market, since all firms get their microprocessors from the same source: concentration increases but no firm comes actually to dominate the market. In the last periods of the simulation, as the microprocessor technology matures, the incentives towards specialization become slightly less compelling and, in some simulations, the mainframe firm and some personal computer producers decide to vertically integrate.

6.2 Testing the model: counterfactuals

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[9] In our simulation we have treated IBM PC as a new independent personal computer supplier, with no link with IBM Mainframes. While this is undoubtedly a simplification, it captures however IBM's strategy to create an independent unit quite separated from its existing mainframe operations. In a previous paper based on a different model, we have discussed IBM's strategy of diversification from mainframes to PC (Malerba et al, 1999)

In order to check the logical consistency of the model and its sensitivity to changes in key parameters, we run some counterfactual simulations. Specifically, we change the values of the parameters of the variables which, according to our assumptions, generate the history-friendly run, and try to answer the following questions:

    a. Does the lack of external markets for components lead to more vertical integration ?.

    b. Do no demand lock-ins in mainframes lead to more specialization ?

    c. Do no demand lock-ins in semiconductors lead to more vertical integration ?

    d. Does a minor technological discontinuity in microprocessor lead to more vertical integration?

6.2.a. The lack of external markets for components induce more vertical integration

First, we concentrate on the size of the external market for components. In the history-friendly simulation, a large external market for microprocessors allowed new semiconductor firms to develop quickly high quality components and to grow large, thereby inducing specialization of computer producers. In this first counterfactual simulation, we eliminate external sales for component firms. Results are shown in Figure 2. In the transistor period, no large differences are observed as compared to the history-friendly simulation. After the introduction of integrated circuits, vertical integration by the large dominant mainframe monopolist takes place somewhat faster. The technological discontinuity associated with microprocessors induces again vertical dis-integration for a short while. Here however the market for the new microprocessor firms is very limited due to the lack of external markets. Thus the signing of a contract between the large dominant mainframe firm and a component producer generates almost monopoly in the semiconductor market. But, when the contract expires, vertical integration by the mainframe producer occurs again, a large demand to the single semiconductor producer disappears and concentration in the semiconductor market falls as a consequence. This tendency is soon reversed as the demand by PC firms induces selection. Moreover, computer firms – both mainframe and PC producers – show a faster and stronger drive towards vertical integration. In the long run, at the end of the simulation, concentration in all markets is not different from the history friendly simulation, but vertical integration is: there is vertical integration in mainframes and often in PCs.

// FIGURE 2 ABOUT HERE //

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6.2.b. No demand lock-in effects in mainframes lead to more specialization

Lock-in effects in the demand for mainframes are a crucial mechanism creating monopoly power and therefore vertical integration in the mainframe market. In this simulation, we decrease the exponent β_1 on the market share in equation (3) - the demand equation for mainframes -. Results are shown in Figure 3. No monopolist emerges in mainframes and both concentration and vertical integration grow slowly in the transistor period and in the integrated circuit period. In turn, the Herfindahl index in the semiconductor market reaches higher levels as compared to the history-friendly run. The third technological discontinuity in semiconductor has no effects on concentration in mainframes, which continues to grow very slowly and remains on low levels. Also vertical integration remains very low. Conversely, concentration grows steadily in the component market, reaching a marginally higher level by the end of the simulation as compared to the history-friendly simulation.

In sum, the absence of strong lock-in effects in the demand for mainframes removes the tendency towards the monopolization of this market. As a consequence, mainframe firms tend to specialize more frequently as compared to the history-friendly simulation.

// FIGURE 3 ABOUT HERE //

6.2.c. No demand lock-ins in semiconductors do not necessarily lead to more vertical integration

In these runs, lock-in effects in the semiconductor market are eliminated. Results can be seen in Figure 4. The change produces no effects in the transistor and integrated circuits eras, where vertical integration of computer firms implies a very small demand for components and hence little room for the lock-in effect to exert its impact. Instead, as expected, concentration in the microprocessors market decreases significantly as compared to the history-friendly simulation. However, the vertical scope of computer firms remains unsurprisingly unchanged, given that specialization occurred also in the history-friendly run. This case shows that external markets and (only in the early period) the technological turbulence associated with the major discontinuity of microprocessors - more than concentration in the microprocessor industry - are relevant factors for maintaining a low frequency of vertical integration of mainframe producers and complete specialization by personal computer producers. Thus, in spite of the more competition in the microprocessor industry, the size of microprocessors producers becomes so large due to the presence of large external markets that computers producers most of the times do not vertically integrate.

// FIGURE 4 ABOUT HERE //

6.2.d   A minor technological discontinuity in microprocessors leads to more vertical integration

In the history-friendly simulation, the introduction of microprocessors implied a significant increase in the merit of design of components compared to the previous types of semiconductors. Figure 5 shows the results. In these runs, the magnitude of this discontinuity is reduced, by decreasing the value of the initial merit of design of microprocessors. The consequences are dramatic. During the last period, the mainframe producer does not specialize and continues to be

vertically integrated into semiconductors. Also personal computer firms (to a lesser extent) tend to vertically integrate. Vertical integration induces also higher concentration in the PC market, because some of the vertically integrated PC firms grow while some specialized PC firms which did not choose advanced microprocessor producers exit the market. In the semiconductor industry, the increasing vertical integration of personal computer producers reduces concentration for the mechanism discussed above: the reduction in demand from the personal computer producers that integrate takes away a large demand to the best semiconductor producers. Therefore the other semiconductor firms increase their market share and concentration declines.

// FIGURE 5 ABOUT HERE //

7. Conclusion

The model is able to reproduce the main stylized facts of the patterns of competition and vertical integration in the computer and semiconductor industries. In addition, it responds to changes in the key parameters in the counterfactual experiments consistently with the hypotheses and the reasoning that are at the core of the model

The model illustrates how the patterns of vertical integration and specialization in the computer industry change as a function of the evolving levels and distribution of firms' capabilities over time. Three specific conditions – the size of the external market, the magnitude of the technological discontinuities and the lock-in effects in demand – exert critical effects and feedbacks on market structure and on the vertical scope of firms as time goes by.

More generally, the model shows how vertical integration and specialization depend on the co-evolution of the upstream and downstream sectors.
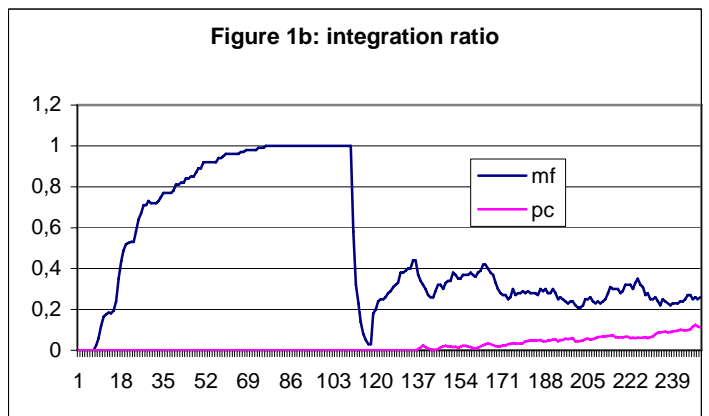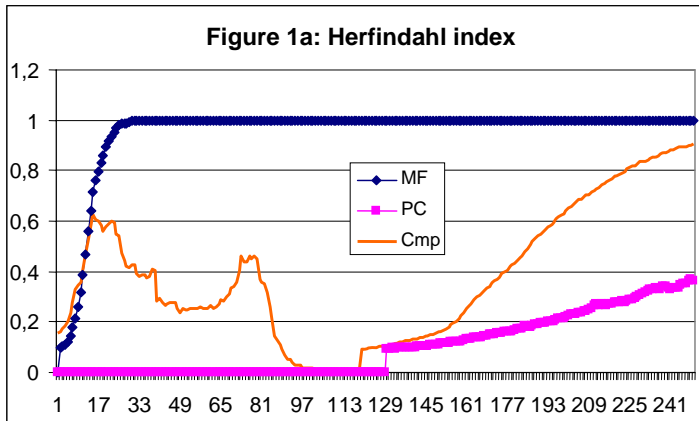
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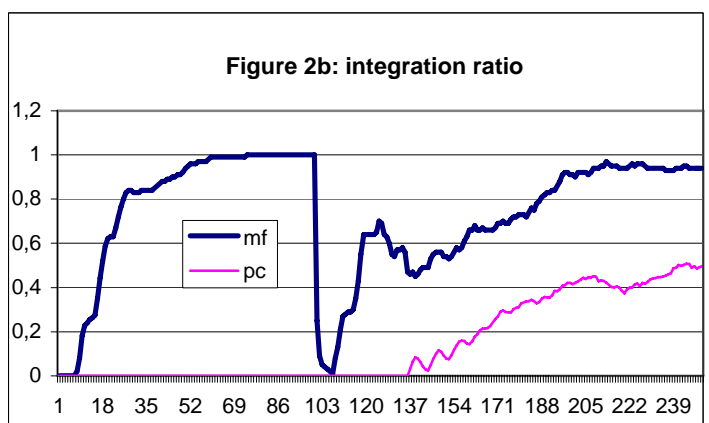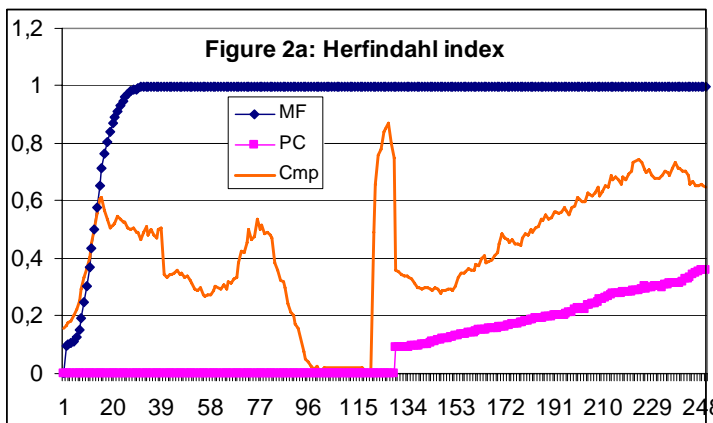
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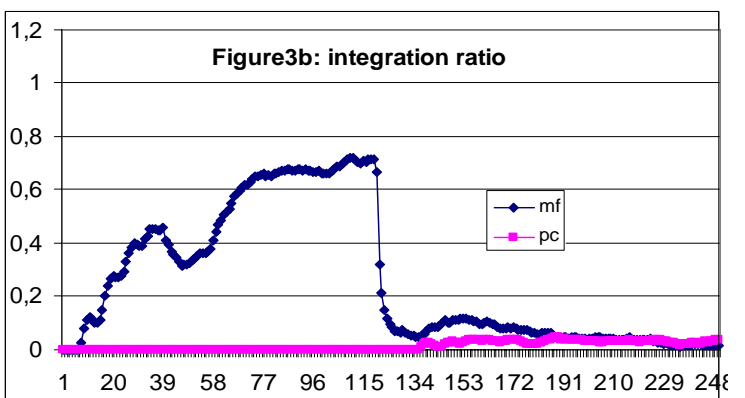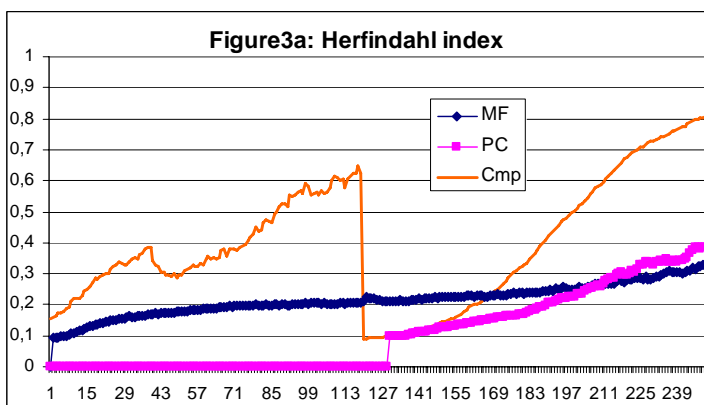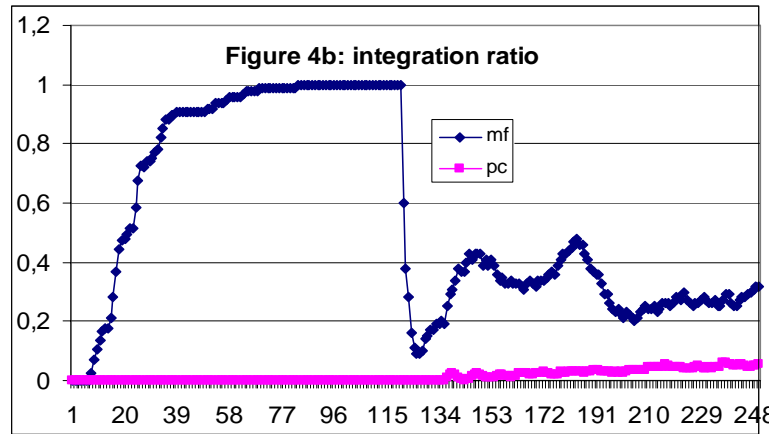
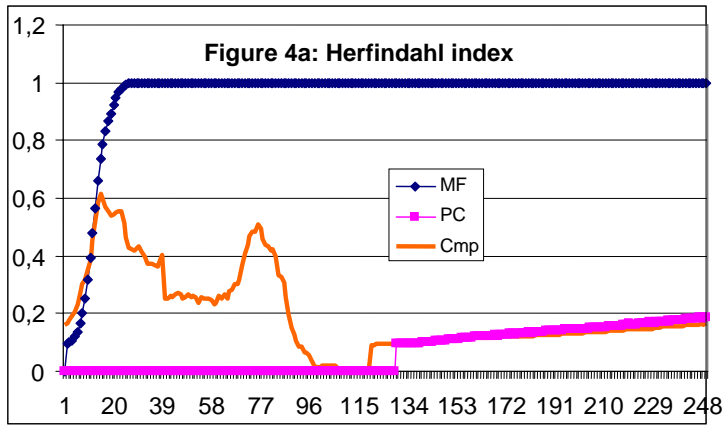## Figures

1. History-friendly simulation

Figure 1a: Herfindahl index

Figure 1b: integration ratio

2. Lack of external markets for semiconductors

Figure 2a: Herfindahl index

Figure 2b: integration ratio

3. No demand lock-ins in mainframes

Figure3a: Herfindahl index

Figure3b: integration ratio

4. No demand lock-ins in semiconductors

Figure 4a: Herfindahl index

Figure 4b: integration ratio

5. Minor discontinuity in microprocessors

Figure 5a: Herfindahl index

Figure 5b: integration ratio

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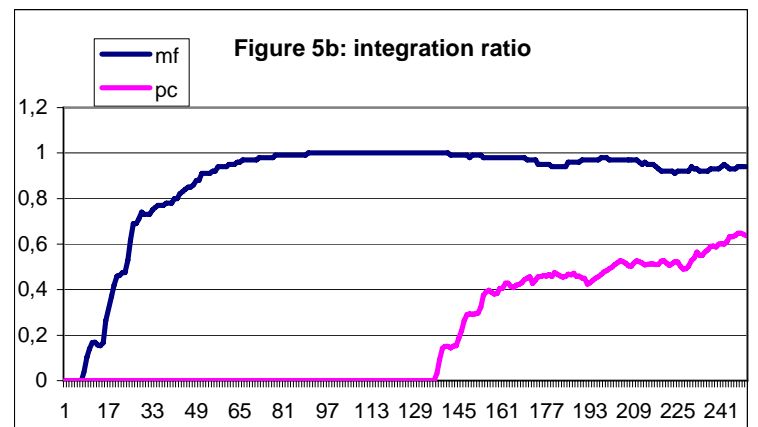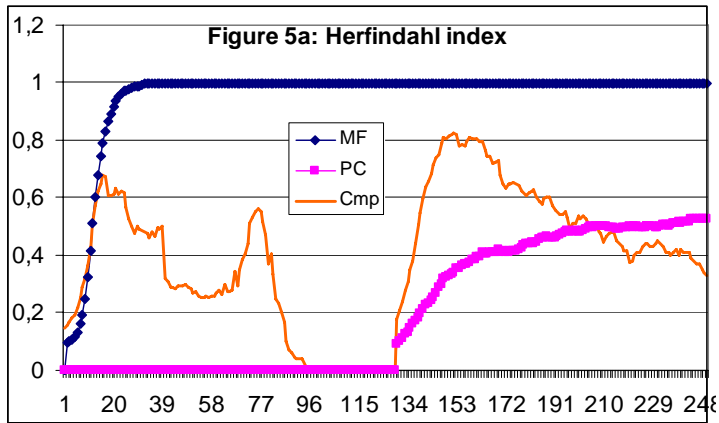
We provide here a complete list of the notation used in the model

Indices:
- i index for firms, $i = \{1,..,I\}$
- t index for time periods, $t = \{1,...,T\}$
- mf, pc, tr, ic, mp indices for type of firm

General model parameters:
- $T = 250$ time horizon
- tc date of introduction of a new component technology : $tc_{TR} = 1$
  $tc_{IC} = 40$
  $tc_{MP} = 120$
- $T_{PC} = 130$ date of introduction of PC producers

Exogenous industry characteristics:
- $I = 12$ number of firms, for each group of firms.
- $subm_{MF} = 100$ initial number of submarkets for MF firms
- $subm_{PC} = 100$ initial number of submarkets for PC firms
- $EM_{TR} = 8$ initial number of external market submarkets for transistors producers
- $EM_{IC} = 8$ initial number of external market submarkets for integrated circuits producers
- $EM_{MP} = 1050$ initial number of external market submarkets for microprocessors producers
- $Lcont = 8$ contract length
- $Lint_{min} = 16$ minimum length of vertical integration
- $\alpha 1_{MF} = 1$ weight of merit of design on $L_{i,t}$
- $\alpha 1_{PC} = 1$ weight of merit of design on $L_{i,t}$
- $\beta 1_{MF} = 6$ bandwagon effect for mainframes
- $\beta 1_{PC} = 1$ bandwagon effect for personal computers
- $\alpha 2 = 1$ weight of merit of design on $L_{i,t}^{C}$
- $\beta 2 = 6$ bandwagon effect for semiconductors producers
- $h_{mf} = 0.75, h_{pc} = 0.75, h_{cmp} = 0.75$, weight of merit of design when calculating $\mu_{i,t}$
- K_t level of public knowledge at time t
- $lim_{MF} = 2, lim_{PC} = 2, lim_{TR} = 2, lim_{IC} = 1.12, lim_{MP} = 1.78$ coefficient for public knowledge function
- $\varphi_{SYS} = 0.01, \varphi_{TR} = 0.01, \varphi_{IC} = 0.015, \varphi_{MP} = 0.02$ rates of growth of public knowledge
- $\theta 1 = 1$ in the probability to integrate; $\theta 1$ indicates the rapidity by which a type of component technology becomes obsolete.
- $\theta 2 = 1$ in the probability to integrate; $\theta 2$ indicates the weight given to $q_{i,t}$ relatively to q_t^{C}
- $g = 20$ age of technology divider
- $b = 1$ coefficient for integration probability function
- $a = 1$ coefficient for specialization probability function
- $E = 0.05$ minimum threshold of market share necessary to survive
- $e = 0.3$ weight given to market share in the exit rule

Endogenous industry characteristics:
- A_γ age of technology γ at time t

Exogenous firm characteristics:

- $M^C_{TR,0} = 0.959$, $M^C_{IC,0} = 2$, $M^C_{IC,0} = 25$ initial value of merit of design for each kind of semiconductor
- $M_{MF,0} = 0.959$, $M_{PC,0} = 3.6692$ initial value of merit of design for mainframes and pc.
- $\tau_{MF} = 0.5$, $\tau_{PC} = 0.75$ weight of component merit of design on the whole computer merit of design
- $A = 1$ coefficient for CES function
- $\rho_{MF} = -0.5$, $\rho_{PC} = -0.75$ degree of substitutability of the inputs in the CES function
- $\alpha = 1$ coefficient for the function that indicates the "value" that customers attribute to any specific computer design
- $\delta_{MF} = 0.3$, $\delta_{PC} = 0.7$ weight given to cheapness, depending on the type of costumer
- $\eta = 0.1$ mark-up added to costs
- $\lambda_{mf} = 0.6$, $\lambda_{pc} = 0.6$ mod replication capability when vertical integration takes place
- $v_{MF} = 250$, $v_{PC} = 250$, $v_{TR} = 200$, $v_{IC} = 250$, $v_{MP} = 500$ draw costs for each kind of firm
-

Endogenous firm characteristics:

- $M_{i,t}$ merit of design of a computer produced by firm i at time t
- $M_{i,t}^C$ merit of design of a component produced by firm i at time t
- $M_{i,t}^S$ merit of design of a system produced by firm i at time t
- $w_{i,t}$ value of cheapness of computer i at time t
- $z_{i,t}$ value of performance of computer i at time t
- $L_{i,t}$ propensity of the computer i to be sold to a group of customers at time t
- $Pr_{i,t}$ probability of the computer i to be sold to a group of customers at time t
- $s_{i,t}$ market share of firm i at time t
- $L_{i,t}^C$ propensity of a component producer i to be selected at time t
- $Pr^C_{i,t}$ probability of a supplier i to be selected at time t
- $p_{i,t}$ price of a computer/component produced by firm i at time t
- $\pi_{i,t}$ profits of firm i at time t
- $o_{i,t}$ production cost of firm i at time t
- $d_{i,t}$ number of draws of firm i at time t
- $R_{i,t}$ RD spending of firm i at time t
- $R^C_{i,t}$ RD spending of an integrated firm i at time t
- $\mu_{i,t}$ mean of the normal distribution from which the values of the *merit of design* of system or component are taken
- $q_{i,t}$ sales of a computer firm i at time t
- q_t^C sales of the largest component producers at time t
- $V_{i,t}$ integration probability of firm i at time t
- $Z_{i,t}$ specialization probability of firm i at time t
- $E_{i,t}$ variable compared to the minimum constant threshold of market share E necessary to survive in the market
- $X_{i,t}$ variable that indicates the number of periods in which a component firm does not sell to computer producers

The reported results for the relevant variables on which we concentrate our attention (concentration indexes, the extent of vertical integration and/or specialization, rates of technological change) are the means of extensive Monte Carlo exercises[10].

Moreover, following Dawid et al (2005), we carried on sensitivity analysis on the model by generating 100 different profiles of the key model parameters. The profiles were generated randomly, where each parameter was drawn from a uniform distribution bounded by a conceptually plausible range. Each particular setting for our control parameters was run over all 100 profiles and the results obtained were averaged over these runs. As an additional robustness check we repeated the procedure with another 100 random profiles in the same manner and tested several of our qualitative insights obtained with the initial set of profiles. In all these cases our findings were confirmed by such a check. Summarizing, all the results were found to be very robust under the settings we discussed above, namely 100 distinctly different runs, with profiles based on parameter ranges that were determined by plausibility checks beforehand .

In Table 1 we list the parameters that have been used for sensitivity and robustness analysis, together with their respective ranges given by upper and lower bounds for their values. For each of the 100 profiles we generated, these parameters were independently, uniformly random drawn between these bounds. In Table 2 we show the results related to this random parameter setting.

Table 1

Parameter	Lower Bound	Upper Bound	Parameter	Lower Bound	Upper Bound
$Lcont$	6	10	g	18	22
$Lint_{min}$	14	18	$M^C_{TR,0}$	0.5	1.5
$\beta 1_{MF}$	5	7	$M^C_{IC,0}$	1	3
$\beta 1_{PC}$	0	2	$M^C_{MP,0}$	23	27
$\alpha 1_{MF}$	0.5	1.5	λ_{mf}	0.4	0.8
$\alpha 1_{PC}$	0.5	1.5	λ_{pc}	0.4	0.8
$\beta 2$	5	7	EM_{TR}	6	10
h_{mf}	0.65	0.85			
h_{pc}	0.65	0.85	EM_{IC}	6	10
h_{cmp}	0.65	0.85	EM_{MP}	1000	1100

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[10] The Monte Carlo variance of these variables is typically negligible. This allows us to avoid reporting confidence intervals.

Table 2