Computing

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The computer industry is remarkable for the pace of its technical change during the last half century and for the pace of its organizational change during the 1990s. From its inception in the 1940s, the industry has been characterized by rapid and sustained technical change. Major breakthroughs leading to new uses have punctuated continuous product innovation serving existing uses better each year. For decades, established sellers experienced success based on the persistence of key interface standards linking their proprietary technology to investments by users and by producers of complements. Much of that success arose from these firms' ability to coordinate and direct the wide variety of different technologies—components, systems, software, and networking—that make up computing. At the same time, the industry, opening up new markets, offered opportunities for entrepreneurial firms to pioneer new kinds of computers for new classes of users.

The industry is undergoing even more change in the 1990s, change of a different character. New technologies are being developed and introduced, many by new companies, in an industry organized in a radically new way. The entrepreneurial companies and the established firms no longer coexist but are in direct competition. Extraordinary returns to capital, and to highly skilled human capital—rents—are moving from vertically integrated firms expert in coordinating multiple technologies to clusters of loosely linked specialized firms. This is a revolution in systems of organizing innovation. At the moment, the "Silicon Valley" system of organizing innovation is on the ascent, and the "IBM" system appears to be fading. The change is so radical that one can speak of an old computer industry and a new one (Grove, 1996).

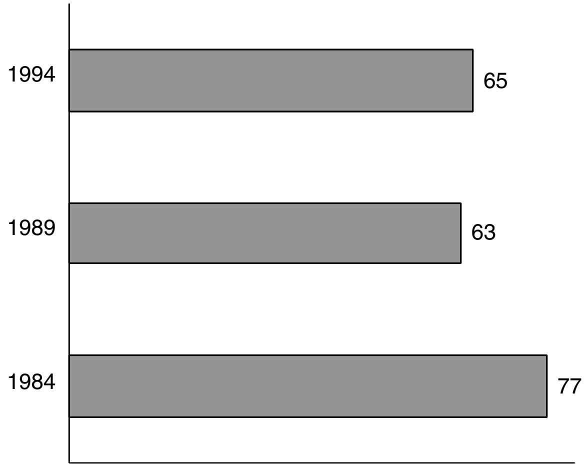

FIGURE 1 U.S. companies' share of worldwide revenues (%).

Despite all this change, one element of continuity is remarkable. Despite the decline of once-dominant IBM, U.S. firms continue to dominate the rent-generating portions of the industry, such as packaged software, microprocessors, and networking. Although the U.S. share of overall industry revenues is slowly falling (Figure 1), rents are staying put. Consider Microsoft, Intel, and Cisco, a troika that is small in revenue share but very large in rents and influence.[1]

This chapter examines the changing structure of the innovation process in computing alongside the enduring dominance of the United States. It examines the sources of the recent changes and the forces allowing a single country to earn most of the producer rents. The change in the character of the industry raises a set of serious questions about the persistence of international technological and competitive advantages in one country and a set of related questions about the origins of technological and commercial success for companies, countries, and regions within countries. Why was the United States, and not some other country, able to profit from the opportunities to become the world technological and competitive leader? What are the key performance characteristics of the IBM model of industrial organization versus the Silicon Valley model? The new computer industry rewards different kinds of technological skills, company organization, and inno-

[1]It would be useful but extremely difficult to turn these anecdotes about the persistence of rents in the United States into a systematic measure. A wide variety of sources, including the financial performance of U.S. and overseas firms, the export market penetration of products made in different countries, and the study of commodity vs. innovative products, strongly suggests that the rents have remained largely in the United States. Yet statistics on production and exports do not permit a systematic answer, partly because the most innovative products are the worst measured and partly because the portion of the industry that earns rents is shifting over time.

vation processes, but how is the United States able to persist in its leadership role despite the changing basis for success? What forces tend to make a single company, or region, a leader in the industry?

For answers one must look at the interrelationships among four very distinct areas:

- technology,
- firm and market organization,
- national support institutions, and
- demand and commercialization.

The necessity for congruence among the first three areas is by now familiar to most readers as a general observation about national success in an industry.[2] To understand the revolution in systems for organizing innovation in the computer industry, we need to understand the new technologies,[3] the new kinds of firms, the new market mechanisms for organizing technology from a wide variety of companies into useful computer systems, and the financial, legal, and educational infrastructure supporting the development of new firms and markets. Clearly the joint and mutually reinforcing development of technology, market structure, firms, and institutions is a source of national competitive advantage. In the computer industry, invention by users is very important. As a result, the forces of demand and commercialization must be included in any analysis of firm or national competitive advantage. Indeed, I categorize computer hardware, software, and networking firms not only by their technological capabilities but also by their marketing and commercialization capabilities. Overall competitive success is typically built upon joint and mutually reinforcing development in all four areas.

Within the United States, there have been several separate and distinct instances of this joint and mutually reinforcing development—separate clusters. On several occasions, a new technological breakthrough and a new kind of demand have combined to touch off new mutually reinforcing developments. The origins of the computer industry had that flavor. So, too, did the origins of the minicomputer industry, the microcomputer industry, and so on. With their different kinds of firms, different technologies, distinct relationships to support institutions, and distinct bodies of demand, each of these is a separate cluster of innovation. They even tend to be located in different regions—the original IBM-centric computer industry in and around New York; minicomputing in and around Boston; and much of microcomputing in California. In large part, the character

[2]See Nelson (1992, 1993) on this with particular regard to the United States.

[3]Indeed, there are some observers, using strongly technologically deterministic modes of explanation, who think that technical change is all we need to examine. Rather than review their arguments in detail in this chapter, I will let them die gently by ignoring them and making it obvious that other assets and factors have been very influential.

of each process, and thus of each cluster, was determined by the demand for the particular computers it made and by commercialization capabilities.[4]

These observations are directly relevant to the contemporary computer industry. Once again, computing is undergoing a revolution in its technical basis, firm and industry organization, and major applications. Networked computing involves transitions such as commercialization of Internet technologies and creation of electronic commerce—transitions that will certainly change the structure of firms and markets and may even mean the end of the vertically disintegrated Silicon Valley system. By their very nature, networked applications are integrative, drawing on technologies and commercialization capabilities from a variety of previously distinct clusters. Firms like Microsoft are proposing a new, more vertically integrated structure for the computing industry, with themselves in leading roles. Meanwhile, uncertainty about the new applications of networked computing opens up entry opportunities. It is a turning point.

The goal of this chapter is threefold. It lays out the structure of innovation in the computer industry, emphasizing the very wide variety in sources of innovation. It then shows how each of the main clusters has organized innovative activity, with an emphasis on the forces—some strong and some weak—that have caused innovative rents to flow to the United States. Finally, it discusses the radical reorganization of the industry and of innovation in the present and its implications for the future international allocation of producer rents.

THE EVOLVING STRUCTURE OF THE INNOVATION PROCESS

An initial look at the major features of the computer industry identifies some aspects that are relevant for the analysis presented in this chapter. The first feature is steady, rapid, and sustained technical progress. Fueled by fast-paced advances in the underlying electronic components as well as in computers themselves, computer hardware price and performance have both improved rapidly.[5] A wide variety of hardware categories have emerged—large and powerful computers such as mainframes, intermediate classes such as minicomputers and workstations, and classes with less expensive products such as personal computers. Technical progress has made the largest computers much more powerful and the smallest more affordable and has increased choice and variety in between. A few pioneering firms once supplied computers; now there are hundreds of successful suppliers of components, software, systems, services, and networks. Performance

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[4] I am indebted to my long-time collaborators Shane Greenstein (see Bresnahan and Greenstein, 1995a) and Franco Malerba (see Bresnahan and Malerba, 1997) for much of this argument.

[5] For an extensive review of measurement studies of computer price-performance ratios, including discussion of alternative definitions of "performance," see Gordon (1989). On any definition of price/performance, improvements of 20-25 percent a year have been sustained over four decades. For a key class of electronic components, semiconductors, see Langlois and Steinmueller (1997) and Malerba (1985). For the complementary technology of software, see Mowery (1996).

increases and price decreases with dramatic improvements in all the different complementary technologies and considerable innovation and learning-by-using by customers. All of these factors woven together by firm, market, and other coordinating institutions have built a multi-billion dollar worldwide industry.

Complementarity: Multiple Technologies, Multiple Innovators

Computer systems draw upon a wide range of distinct, ever-advancing technologies. Computer hardware, software, and networking are capital goods used in a broad array of production processes. As with many general purpose technologies, investments in this capital lead only indirectly to valuable outputs. Without complementary innovations in other inputs or the complementary invention of new computer-based services, computers are useless.[6] At a minimum, to understand innovation in the computer industry, one must examine both invention by sellers of information technology and co-invention by buyers. Co-invention—users' complementary investments in human capital, new products, applications, business systems, and so on—has pulled computing into a wide variety of uses. The uses share invention but vary in co-invention.

Both invention and co-invention are complex processes combining innovations of many different forms. It is not a trivial problem to coordinate the direction of technical progress in invention with that in co-invention. A variety of market and commercialization institutions, ranging from the management and marketing functions in IBM to the markets and standards of open systems computing, have been used for this coordination. The innovation process in computing, dramatically oversimplified, consists of at least the elements described in Table 1.

The table begins with the familiar hardware technologies that most people tend to think of as "computers." Fueled by fundamental advances in materials and production processes, electronic components such as microprocessors and memory chips have seen steady and rapid technical progress. A tremendous amount of innovative effort lies behind empirical regularities such as Moore's law, by which the number of transistors on a cutting-edge integrated circuit doubles every 18 months.[7]

Another large and ongoing innovative effort is needed to bring these electronic components into useful electronic devices. A microprocessor may be the "brains" of a computer—or of a printer, a disk controller, or many other peripheral devices for that matter—but the design of computer systems and related hardware devices is a difficult and demanding piece of invention. It is not at all true

[6]See Bresnahan and Trajtenberg (1995) for analysis of general purpose technologies.

[7]See Langlois and Steinmueller (1997) for an analysis of this inventive process, which includes improvements in materials such as carefully doped silicon, equipment such as etchers and steppers, and the production process for integrated circuits themselves. On the complexities of the latter, see, for example, Hodges and Leachman (1996).

TABLE 1 Schematic of Technical Change in Computing

Invention

Technologies (examples)	Coordination institutions for invention
Electronic components (microprocessor) Computer systems (mainframe, PC) Peripherals (disk drive, printer) Systems software (operating system, network software, database management system) Applications software (accounts payable, computer aided design)	Vertical Integration Interface Standards
	Coordination institutions for commercialization Vendor field sales and service Systems integrator Custom software house Consultant, VAR
Co-invention technologies (examples)	Coordination institutions for co-invention
Applications software (credit-card fraud detection system, spreadsheet macro) New services (sorted checking account statement, instant account balance, frequent-flight bonus program) New jobs and organizations (business process re-engineering, bank teller as sales representative)	MIS Department Systems Analyst CIO

that Moore's law for integrated circuits translates in any immediate and direct way into rapid declines in price-performance ratios for computers or other hardware. Computers themselves have exhibited smooth declines in price-performance ratios only because their designers have conquered a series of bottlenecks in different technical areas.[8] Progress in these areas may come in fits and starts, a choppiness that is smoothed out only when all the various subtechnologies are combined. Furthermore, a series of major technical discontinuities such as the founding of whole new classes of computers has punctuated the smooth advance.

For key peripherals, such as disk drives, major discontinuities and breakthroughs have characterized the process of technical advance.[9] Perhaps that fact should not be too surprising. Technical progress for peripherals is not purely electronic: a disk drive needs extraordinary precision in its reading and writing

[8]See Iansiti (1995) for an analysis of advances in computer systems technology along these lines and for discussion of management structures for dealing with rapid technical change in a variety of subcomponent technologies.

[9]See Christensen (1993) on how these discontinuities have led to major competitive turnover in the disk drive industry. Leading firms have fallen aside and been replaced by new firms. Also see Henderson's (1993) work on semiconductor equipment.

functions, for example; a printer needs a way to deposit ink. Computer hardware uses complex logic components and complex electromechanical components, both drawing on a wide variety of distinct subtechnologies.

All of computer hardware, taken together, draws on a wide array of distinct technologies. Overall, the rate of technical progress in computer hardware of a variety of types has been rapid. In the most innovative segments, technical progress reflects large investments in invention. There appears to be little difficulty with appropriability in this area, as the largest scale economy hardware technologies, such as microprocessors, tend to have quite concentrated industry structures as the mechanism for appropriability. The wide variety of product and process technologies in computer hardware means that some parts of computing have matured and become commodity businesses. In turn, production and to some extent invention, which were once largely confined to the United States, have now become global activities.

Software is a separate set of technologies that make computers and networks of computers useful in a variety of tasks. Systems software is best understood as a general purpose technology enabling a wide variety of distinct applications. Operating systems, network operating systems, communications controllers, and database management systems are as much a part of computers as the relevant hardware, but they are invented separately, and the total effort in their invention is very substantial.[10]

Applications software is a newer category as a market phenomenon (OECD, 1989; Mowery, 1996). For many years, applications were part of co-invention—almost all applications were custom-built for use in an individual company. Suppliers might be a management information systems (MIS) department or "end-user" departments. Now there are several important applications software markets in which software inventors sell their wares to user companies. The largest, in unit sales, are individual productivity applications (spreadsheets and word processors). Other important categories include general business software such as accounting, inventory management, and enterprise resource planning, and "vertical" applications software, which provides computing tailored to the needs of a specific industry. The transition from the co-invention of applications software to applications software markets is incomplete, so Table 1 lists applications software both at the top, under invention, and at the bottom, under co-invention.

To complicate the picture further, intermediaries can play the same role. A variety of commercialization institutions bridge the gap between invention and co-invention. Custom software, written for one customer at a time, existed as a market sector from the earliest days of computing. This service is sometimes

[10]The rate of technical progress in systems software is difficult to measure separately from the rate of technical progress in computer systems, because the two are such close complements. The measures of technological progress in computer systems shown in Table 2 should probably be interpreted as covering systems hardware plus operating systems but not other fundamental systems software.

sold as consulting, sometimes as explicit custom software, sometimes performed by systems integrators, and sometimes bundled with inventors' products as field sales and service. I list it here almost as an afterthought, as every one does. But that is an analytical mistake. By recent estimates, the "computer services" industry is larger in revenues than the software industry.

Why is this sector so large? It is difficult to plan, implement, and use computerized business systems; it is hard to manage computer and telecommunications departments in support of core businesses; high-quality computer personnel are scarce and expensive; and making strategic use of information technology is complex and sometimes fails. Using companies' Management Information Systems (MIS), departments of chief information officers (CIO) turn to the diverse computer services industry for support and help. Buyers choose between service firms whose initial competence was in the information technology arena, such as EDS or IBM's ISSC unit, in competition with others from the business consulting world, such as Andersen. Some users outsource their management information systems; others outsource their entire operational departments that use computers intensively, such as payroll processing (perhaps to ADP), or bank credit card (perhaps to First Data).

How Much? How Fast? How Well?

Table 2 presents some information on the sizes of the sectors just discussed and on their rate of technical progress. The main purpose of the table is to dramatize the wide variety in sources of innovation in computing. The table once again shows invention at the top, commercialization/intermediation in the center, and co-invention at the bottom.

The boundaries and definitions behind these tables are subject to some dispute, but a large message is clear from the size figures. A very substantial fraction of the activity in the industry is farther down the table, in commercialization or co-invention. The figures for the invention and commercialization segments reported in Table 2 are worldwide sales of those sectors.[11] They include both the costs of inventing new information technology and the costs of the goods, such as computers, in which that invention is embodied. Co-invention is harder to measure. The most objective part of it is programming personnel expenditures in computing departments, and this is the figure in Table 2.[12] The commercializa-

[11]This follows International Data Corporation (IDC) definitions and uses their 1996 report.

[12]The budget figures in Table 2 represent aggregate expenditures of using companies on their computer departments, less the products and services they buy and lease. These are primarily expenditures on programming personnel and cover the costs of writing applications programs in corporations, maintaining them, and so on. Some of the other expenditures counted here are training, planning systems, and the like. These costs count only the part of co-invention that is centralized and professionalized in MIS departments. If the finance department writes a spreadsheet macro on its own budget, or if the marketing department hires a webmaster on its own budget, it is almost certainly not counted here.

TABLE 2 Market Size and Rate of Technical Progress in Major Computing Industries

Technology	1996 Worldwide market size ($billion)(IDC)	Technical progress
Invention		
1. Electronic components (microprocessor)	(included in 2.)	Rapid—Dulberger (1993)
2. Computer systems (mainframe, PC)	261+	Rapid—Gordon (1989)
3. Systems software and tools (operating system, network software, DBMS	48+	(unstudied)
4. Applications software (accounts payable, CAD)	48+ combined (4. and 5.)	(unstudied)
5. Applications software (spreadsheets, word processors, etc.)		Slower—Gandal (1994)
Commercialization		
6. Computer and software services vendor (billed) services; systems integrator; custom software house; consultant	176+	(unstudied)
Co-invention		
7. Applications software (credit card fraud detection system, spreadsheet macro)	310+	Slow and difficult—Friedman (1989)
8. New services (sorted checking account statement, instant account balance, frequent flight bonus program)	Together larger than 7—Ito (1996) Very substantial—Brynjolfsson and Hitt (1996); Bresnahan and Greenstein (1995b) (8. and 9.)	Slow and difficult—Barras (1990); Bresnahan and Greenstein (1995b)
9. New jobs and organizations (business process re-engineering, bank teller as sales representative)		

*See footnotes 11 and 12 for International Data Corporation (IDC) sources and my calculations based on them.

tion services shown in the table are measured by their sales. Most of these charges are for activities, such as custom software and service, integration, or maintenance, that user companies might have done themselves.

An important part of co-invention is not measured at all in Table 2—the co-invention of new products and new processes based on computing. For example, much of the new product and process innovation in the services sectors is computer-based. The table measures only the part of this innovation that is explicitly computer programming. The equally important but unmeasured innovation is invention of new tasks for the computer. A new customer service—getting your balances by calling your bank on the telephone at night—will typically be invented and designed by marketing people. A new organizational structure—permitting the telephone bank operators to resolve certain account problems in those same account-query phone calls—is typically invented by operations managers, not the computer department. No firm accounts these activities as R&D, but they are an important part of innovation.[13]

Although these activities are not easily measured, a substantial anecdotal literature shows that inventing tasks for computers to perform and coordinating the efforts of a corporation's technical people with those of its marketing or operations people are difficult activities that consume a great deal of inventive energy.[14] There is also indirect quantitative evidence for the importance of these costs. Bresnahan and Greenstein (1995b) examined computer user's demand for a major new technology. Ito (1996) looked at major upgrades to existing computer systems. Brynjolfsson and Hitt (1996) considered the increases in sales per unit cost of companies that make new investments in computers. All these approaches reveal substantial costs of inventing the business side of computer applications.[15]

The last column in Table 2 offers a view of the rate of technical progress in the different portions of computer industry invention. As one reads down the column, the measured rates of technical progress fall. Hardware technical progress has been stunning, software technical progress has been rapid, and technical progress in co-invention has been slow. One implication of this variety is that the aggregate rate of technical progress in computing is slower than the rate of technical progress in hardware, dragged down by the large and slow co-invention sector.

The causes of the variety are important. In computing, technical progress in the applications sectors is slower than it is in the general purpose technologies. Technical progress in the general purpose technologies is difficult but has an excellent science and engineering base. Because of their generality and the growth in computer use, especially business computer use, general purpose technologies have huge markets that, partly as a function of available intellectual property protection tools, have provided strong if risky profits. Applications have a less well-developed science base, tending to draw on the business school's knowledge of organizations rather than the engineering school's knowledge of

[13]This is an example of the general problem of measuring innovation and productivity in services. For the computer-based production process, see Barras (1990).

[14]Friedman (1989) gives an interesting history of this.

[15]The substantial costs of co-invention have led some observers to doubt that companies' investments in computers and other information technology have been useful. This concern has led to a large and, in my judgment, hugely misguided literature on the "productivity paradox." Computers are useful. What is doubtful is the accuracy with which the output of the service sector is measured. Computers appear to be low productivity investments only when those measurements are assumed to be accurate.

circuits, bits, and bytes. The very nature of computer applications makes scale economies difficult to achieve. And bridging between technology and business purpose has proved conceptually difficult. The implications of the variety are also important. In this particular general purpose technology, the problem of innovation incentives does not arise in appropriability for the general purpose or generic technology. Instead, it arises in the applications sectors.

The Organization of Innovation

Managing the disparate technologies so that they work together has not been a trivial matter. Two main management structures have been deployed historically (see the right side of Table 1.) One is the *vertically integrated technology firm*, such as IBM. In it, a management structure is in place to coordinate the joint development of the many distinct technologies that make up computing. The other management structure is less centralized and explicitly coordinated. In the "Silicon Valley" form, distinct technologies are advanced by a wide number of different firms. Interface standards, cross-company communication, and markets have been used when supply is by a *group of vertically disintegrated specialty technology firms*.[16]

The emergence of applications software markets with independent "packaged" software vendors acting as suppliers was not merely a technological event.[17] It involved changes in industry structure and business models to be effective. Because software is a business with increasing returns to scale, the existence of a large number of computers on which the same program could run encouraged the emergence of software companies—first custom and then market. The invention of the computer platform by IBM in 1964 was a landmark event. Computers within the same platform have interchangeable components. Interchangeable components across computers of different sizes also permit growing buyers to use the same platform over time, avoiding losses on long-lived software. The invention of the platform and the creation of new platforms in minicomputing, personal computing, and so on improved the economics of software by permitting exploitation of scale economies. Some of these platforms are more "open" than others, so that control of the interface standards determining what software runs on the platform is spread out among many sellers, including "independent software vendors." The packaged software business that results is primarily American, with considerable invention and a large export market.[18]

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[16]Although this form is named for the region that brought it to a high art, not all firms that participate in Silicon Valley innovation are located there. Many computer platforms with strong links to Silicon Valley nonetheless have key components supplied elsewhere in the United States (Washington State, Texas) or worldwide (Taiwan).

[17]See Steinmueller (1995) for a penetrating analysis.

[18]This stands in contrast to custom software, in which a great many sellers are local to particular countries. The importance of customer connections is the likely explanation. See Mowery (1996).

The trend so far has been to a more vertically disintegrated organization for innovation. This has had the considerable advantage of permitting specialization, including some international specialization. It has also increased the number of companies that can invent new and useful computer technologies. Yet the trend is by no means absolute. In the next section, we turn to the forces that have permitted the vertically integrated and vertically disintegrated systems of organization to exist in parallel for many years.

Co-invention has also been reorganized,[19] and much of co-invention has been shifted from end-user companies to commercialization or software companies. The latter trend parallels the vertical disintegration of invention and permits gains from specialization and scale economies.

This completes our tour of the different agents in the computer industry. The important message is that innovation in this industry is spread out over a wider range of economic agents than one might have imagined. This variety has been organized both by the IBM model— extended to influence over customers—and the Silicon Valley model.

DIFFERENT TYPES OF DEMAND

The variety in types of demand served by computing has had an important influence on the development of supplying firms and on markets. Several very different kinds of *demand* and *use* are important here. First is *business data processing in organizations*. Typically, the applications of computers in this domain involve changes in white-collar work across an organization. The demanders are senior managers seeking cost control or new ways to serve customers; they are supported by professionalized computer specialists. A second kind of demand is that for *business individual productivity applications* on PCs. More and more white-collar workers have seen their work at least partially computerized by these applications, but the span of the application tends to be a single worker. The third demand is for scientific, engineering, and other technical computation. Served by supercomputers, by minicomputers and later by workstations, and by PCs, factories, laboratories, and design centers do a tremendous volume of arithmetic. In total, the *technical computing* market size is roughly as large as each of the two kinds of commercial computing described above. Computer networks have changed technical computing through developments such as the Internet.

Computer networks have also changed business computing. *Interorganizational computing* links together firms or workers in distinct organizations. Applications such as networked commerce, electronic data interchange, and on-line

[19]Some of the organizational changes are shown in the Coordination Mechanisms column of Table 1. It is hard to say that this series of changes has much improved performance in co-invention. See Friedman (1989).

verification of a credit-card holder in a store, for example, are now the most rapidly growing part of computing.

This variety in demand has permitted the emergence of *different suppliers and markets*. More important, demand variety has permitted the emergence of new, entrepreneurial firms in parallel to established ones. In the next sections, we take up the distinct clusters of invention and co-invention that have arisen to serve the three oldest parts of demand and then turn to the question of American dominance of those very distinct clusters. The newest demand, interorganizational computing, involves both a blurring of the boundaries between the clusters and another set of reasons for American dominance, so current developments are treated in later sections.

ORGANIZATIONAL COMPUTING

The oldest part of the computer industry, mainframe computers, consolidated around a dominant firm (IBM) and a dominant platform in the 1960s, most likely because IBM had created the best combination of supplier firm, market organization, technical standards, and technical progress to support business data processing in organizations.[20] IBM emerged from an early competitive struggle to dominate supply, in the process determining the technologies needed for computing, the marketing capabilities needed to make computers commercially useful, and the management structures that could link technology and its use. Within organizational computing IBM managed both the cumulative and the disruptive/radical parts of technical change. Customers' learning by using and IBM engineers' learning by doing were focused on the same IBM computer architectures. IBM was not only the owner of established technology but also the innovator of the new.

From the mid-1960s onward, IBM dominated organizational computers with a single mainframe platform that began as the IBM System/360. This historical experience is important because it reveals some of the forces leading the computer industry to have only a very few platforms, even today. And the question of how open those platforms would be—that is, the extent to which a single firm would control and profit from direction of the platform—is timeless.

The key to IBM's invention of a platform was operating system compatibility across computers with different hardware. Because the same IBM software worked on all models, application software and databases on one system could be moved easily to another. IBM invented technical standards for how the products worked together and embedded them in its products. Further, the company had a

[20]The boundaries of the mainframe segment are not clear. Commercial minicomputers, which are not treated in this paper, eventually became much like mainframes. For international comparison purposes, the commercial minicomputer segment can be thought of as an extension of the mainframe segment.

field sales and service force to help users choose and configure computers and then make new, compatible, purchases when their use expanded.

Total investments by IBM and its customers in platform-compatible components were large, sunk, and platform-specific.[21] Those three features were then, and are now, powerful forces that limit the number of platforms that will serve any particular demand. "Platform-steering" vendors, such as IBM, create customer value as well as dominant positions for themselves.[22] IBM dominated organizational computing from its inception until the beginning of the 1990s, investing heavily in new technology, both hardware and software. When technical progress meant that existing IBM technologies were outdated, the company routinely abandoned its earlier investments in order to move forward. IBM's users decided, again and again, that it was better to stay with the established IBM platform than to switch to another. As a result, control of the direction of the platform and its standards remained completely centralized. Users did not have much in the way of competitive choice, but their investments were preserved. The inventive efforts of other participants in the platform—customers, user groups, and third-party providers of compatible components—made the platform better. A platform is a virtuous cycle of positive feedback, as more invention by customers, by third party providers, or by IBM encouraged further invention by the others. This was to all participants' advantage but notably to IBM's.

Economists often focus on the persistence of dominant firms in this industry. To understand the international industry structure, however, it is far more important to look at their origins. What was the origin of IBM's position, and what does it have to say about the sources of U.S. rents?

Despite substantial early enthusiasm about the potential for computers, there remained throughout the industrial world fundamental uncertainty on the technological development of the industry, the range of applications, and the potential size of the future market (Rosenberg, 1994). In particular, it was unclear whether the largest demand segments would be military, scientific and engineering, commercial, or something else altogether. These uncertainties in turn meant that the most important directions for technical progress as well as the nature of buyer-seller relationships and of commercialization efforts were unsettled.

As a result three distinct types of firms entered the early computer industry: office equipment producers, electronics firms, and new firms. Computers were a new electronics good that attracted several producers already active in other electronics fields. Similarly, some of the first applications of computers were in business, attracting firms with established connections to business data processing. This tension between technology-based and market-oriented firm organizations and competencies is ongoing (Davidow, 1986). The three groups of en-

[21]See Bresnahan and Greenstein (1995a) for more complete discussion and sources.

[22]Then and now, there has been a debate over the advantages of the customer value vs. the disadvantages of the dominant position.

trants had distinct capabilities and distinct strategies, but the capabilities and strategies of each group were similar in Europe and the United States (it was too early in the technological development of Japan for competition from that country to play much of a role). The electronics-based firms faced the challenge of either building or acquiring a business-equipment marketing capability—including a substantial field sales force—or finding a way to succeed without it. Firms with business equipment capabilities needed to add technological ones.

The combination of technical drive and customer focus required new management structures. IBM's success sprang from its major R&D investments and, more generally, its adherence to the Chandlerian three-pronged investment strategy (managerial capabilities, technology, and commercialization).[23] IBM rapidly became the world market leader because of its continuous R&D effort in developing new products, combined with advanced manufacturing capabilities, excellent marketing competence, and management structures keeping technology and market aligned. In Europe IBM's superiority in products and customer assistance was coupled with a local presence on the main markets. IBM Japan was for a long time first in revenues among "Japanese" computer companies. IBM used the "IBM World Trade" model, making itself everywhere as local a company as possible.

The Sources of U.S. Advantage in Organizational Computing

As the IBM experience illustrates, firm-level sources of national advantage have proved very important in organizational computing.[24] Of course, a wide variety of institutions and policies supported the emergence of IBM as the world market leader.

Universities

Universities in both the United States and Europe were active at the scientific and prototype levels before computers were commercialized.[25] In the United States, universities were less important for their scientific and engineering contributions that would be useful in computing than for their participation in computer projects for military and commercial sponsors. This created not only a body of knowledge but also a flow of trained people.[26] University research and university

[23]See Usselman (1993) and Chandler (1997).

[24]This is consistent with the simplest and most basic theory of international rent-steering in imperfectly competitive industries. If equilibrium in the industry leads only a few selling companies to earn rents, then the nations in which those companies are located will gain producer rents.

[25]This era is discussed in far greater detail in Bresnahan and Malerba (1997).

[26]See Flamm (1987) for a careful history of the American and European technology development efforts.

people did not provide the key competitive advantage to any country, but their absence would have created a bottleneck.

Government's Role

Substantial government backing for the early U.S. computer industry offered advantages to firms in the United States. Federal, especially military, research funding backed many of the purely technical capabilities needed to build computers (Flamm, 1987). Further, many early U.S. computer systems were themselves directly supported by federal funds. It was clear that the military was going to purchase many computers from domestic suppliers. All this encouraged development in the United States.

There is little support, however, for the view that the U.S. government "bought success" for IBM, and no support whatsoever for a "strategic trade policy" view of U.S. government actions (Bresnahan and Malerba, 1997). U.S. government actions were far removed from intentional strategic trade policy aimed at creating a "national champion." The ultimate national champion, IBM, was not an important part of the defense effort, nor was defense funding all that large a portion of IBM's commercial computing initiatives. The Defense Department spread a good deal of money around and let the supplying industry structure emerge in the marketplace.[27]

Antitrust Policy

U.S. antitrust policy worked actively to prevent IBM from emerging as the dominant firm in the fledgling computer industry. In particular, the U.S. Department of Justice systematically opposed IBM's strategy of strengthening commercialization and technical capabilities within the same firm. The department was not particularly anti-IBM nor anti-large-firm, but it did object to aspects of IBM's three-pronged strategy as anti-competitive. A 1956 consent decree between IBM and the government limited IBM's effectiveness as a commercialization company. A second antitrust lawsuit, brought in 1969 and contested for more than a decade, viewed IBM's service, sales, and support efforts as anticompetitive lock-in devices. The legislative branch also tilted procurement policy against IBM.[28] The point here, again, is that the industry structure leading to U.S. dominance was not the invention of the government.

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[27]Usselman (1993) offers a very interesting argument that U.S. procurement policy favored IBM only because it took this form. IBM would not likely have been chosen as the national champion in the critical early phases, nor would a "supply side" procurement policy have led to the development of the IBM commercialization capabilities.

[28]There is an active debate on whether government agencies were able to evade the law and procure from IBM as they saw fit. See Greenstein (1993). There is no debate about the anti-IBM policy itself.

Albeit mostly by accident, antitrust policy was helpful in creating an independent software sector. The partial unbundling of IBM platforms meant that firms other than IBM could sell into IBM-using sites more easily. At the same time, the United States has had comparatively strong intellectual property protection for computer hardware and software. Countries with weaker protection have been less successful in software supply.

Intentionally in this case, the same antitrust policies led to a multicompany basis for the U.S. hardware sector, at least in the peripherals sector. The emergence of mass-storage device sellers (PCMs) other than IBM undercut IBM's ability to price discriminate using storage as a metering device. And it increased the variety and flexibility of hardware supply in the United States.

Competition from Other Countries

During the long period of IBM's hegemony, other companies sought a share of the worldwide market for organizational computing. In Europe and Japan, governments used trade and procurement policy to protect their weak domestic firms from IBM. These governments also influenced large quasi-governmental buyers in European and Japanese markets, principally banks and telephone companies, to buy domestic computers rather than IBM imports. In Europe this protectionism was no more than a barrier to exit, slowing the ultimate decline of European firms.

Japanese firms and the Japanese government came closer to creating an effective barrier to IBM's dominance.[29] Instead of a national champion policy, the best of half a dozen competing members of government-sponsored consortia would receive government support. The policy was technologically flexible. After some initial failures at making a purely Japanese computer, IBM compatibility became the focus. The effects of the consortia were to build a very substantial hardware technological capability within some Japanese firms, partially catching up to IBM. Developments on the software side were far weaker.

TECHNICAL AND PERSONAL COMPUTING: DISTINCT MODELS SUCCEED IN NEW SEGMENTS

A second set of U.S. computing successes served different markets and drew on different national capabilities and institutions. Although these two new areas, minicomputers and microcomputers, shared some fundamental technical advances with the existing mainframe segment, considerable innovation and entry characterized each new segment's founding. The two segments, minicomputers and microcomputers, developed new markets and organizational structures. The

[29]This very abbreviated treatment draws heavily on Anchordoguy (1989), Fransman (1995), and Bresnahan and Malerba (1997). See the last reference for a discussion of Japanese near-success.

"technologies," as engineers use that term, of each of these segments were distinct. These new kinds of computers served new kinds of demand. Accordingly, co-invention and commercialization in these markets were distinct. A very different form of firm and market organization characterized supply in the new segments, and supply was from new firms. With distinct invention, co-invention, and markets, these new segments formed new clusters of positive feedback and changed the face of competition within the industry.

Technical Computing

The first of these new segments was *minicomputers*, machines that from their start in the late 1950s were intended for scientific and engineering use.[30] Most of the firms in technical computing were entrepreneurial start-ups, many with their origins in universities. DEC, the largest of these start-ups with about one-third of minicomputer sales over many years, had its origins at M.I.T.'s Lincoln Laboratory. Other firms originated in the instrument business. Hewlett-Packard came out of both fields.

A series of reasons led this segment to be served by a distinct cluster. The appropriate seller commercialization model for manufacturing and scientific minicomputers was built on the fact that the relevant buyers were technically fluent. Software support came not from minicomputer producers but from "third parties," notably value-added resellers (VARs) and consultants, or from the end users themselves. The technical computing segments were focused on raw technology, low commercialization cost, and dramatic progress in computer price/performance ratios. The sources of national advantage for the United States came from universities and from the cluster of financial and other institutions supporting entrepreneurship. After a time, the minicomputer business itself became one of the supporting institutions, as later entrants were often spin-offs from existing minicomputer firms.

Personal Computing

The second new segment was the personal computer, which developed starting in the mid-1970s in the United States on the basis of hobbyist demand. Early entrants resembled those in minicomputers—established electronics (but not computer) firms and de novo entrants. Entrepreneurs entered not only computers, but also other hardware components and software. Positive feedback among these different entrepreneurs led not only to their success, but also to a pronounced regional advantage for the western United States, and the available support institutions for entrepreneurship in that region, such as venture capital, both rein-

[30]The boundary between organizational and technical computing is unclear. Early minicomputers and later supercomputers and workstations were not in competition with IBM, however.

forced and were reinforced by the new cluster of entrepreneurs.[31] The original location of personal computer suppliers in the U.S. was encouraged by forces similar to those in technical computing but quite dissimilar from those in organizational computing.

Few of those original firms in the PC business survive, and fewer still continue to earn rents. Yet the supplier rents in the PC business remain in the United States. What were the key competitive forces that permitted the replacement of early success stories yet left the rents within the same country?

Competition in Personal Computing

By the mid-1980s the structure of supply and demand in personal computing had unleashed three powerful new forces that affected competition.[32] These forces were unanticipated, so they presented very considerable opportunities for profit to the firms that first understood them. First, vertical disintegration of supply meant *divided technical leadership*. Second, large unit sales increased the importance of *scale economies*. Third, suppliers were capable of, and demanders of PCs were eager for, *speed-based competition*. These forces changed the way long-term features of computer market equilibrium, such as network externalities and positive feedback, played out in the PC market. These changes would matter not only in PC but also in networked computing. The technological leadership determining the direction of technical advance of the PC came to be divided among four distinct sectors of PC computing:

1) Makers of computers, of which IBM was the largest and most influential;
2) Intel, leading maker of the microprocessors in the PCs;
3) Microsoft, maker of the dominant operating system for PCs; and
4) Applications software makers such as Lotus, WordPerfect, and Ashton-Tate.

This divided technical leadership is striking for two reasons. First, it was remarkably effective at advancing the PC platform. Divided technical leadership meant rapid advance from specialists and the ability to take advantage of external economies among sellers and users (Langlois, 1990). Second, divided technical leadership is remarkably competitive. Each of the firms named above achieved, at least for a time, a position of dominance or even of near-monopoly in its pri-

[31]The early 1980s saw the aging of the original personal computer platforms and a standard-setting opportunity. IBM introduced the IBM PC and, for a while, controlled the new standard. IBM entered through external linkages with competent firms and with an open architecture. Although the PC was a product from long-established IBM, the majority of IBM's complementors were entrepreneurial, many university-based. Thus the invention of the IBM PC did not convert the personal computer business into one like the mainframe business.

[32]Several of these were the result of IBM's decisions at the time of its entry into the PC market. Yet nobody saw the competitive consequences at that time.

mary product. Yet each felt, or was substantially harmed by, competition from producers of complements. This new vertical competition—competition in which producers of complements attempt to steal one anothers' rents—is an important feature of PC markets and is likely to characterize all future computer markets. In most industries, competition comes from horizontal directions, that is, from firms selling substitutes.[33]

Vertical competition can be powerful, as demonstrated by the transition from the "IBM PC" (control of the PC business by IBM) to the "Wintel" (control by Microsoft and Intel). Attempts by Lotus and WordPerfect to earn operating system rents in their applications programs, spreadsheets and word processors, were vertically competitive initiatives. Operating system vendor Microsoft also engaged in vertical competition and succeeded in taking most of the rents of the IBM, Lotus, and WordPerfect products.[34] Microprocessor manufacturer Intel has destroyed the economic basis for many board-level products by including their functionality in new versions of the computer's "brain." There are many other examples in which firms in the PC industry whose products are complements in the short run are in competition for the same rents in the long run. The important elements of this vertical competition are standards stealing, time-based competition, and racing for rents.

Why is there vertical competition? First, vertical disintegration provides a source of competitors that is not available when a vertically integrated firm supplies the complements. Second, boundaries between vertical product segments are inherently malleable and thus subject to manipulation. Most important, the control of key interfaces directs the flow of producer rents. So producers compete for control of future boundaries between their products and thus future rent flows. The newfound importance of *scale economies* in PCs underscores this vertical competition. Unit sales in PC markets are very large by the standards of computer markets generally. Another force, less often mentioned but equally important, is the importance of a few key applications in PC use.

The final novelty in PC competition is perhaps its defining character—speed-based competition. The de facto standard-setting process favors early firms in the market for several reasons. First, once customers have made their co-investments, the standards in use tend to persist. Thus there is first-mover advantage, a substantial motivator for races. Races are particularly likely to occur when there are new opportunities, such as the Internet. Incentives to improve products, and to do it quickly, are very high.

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[33]The most important example of horizontal competitive innovation in PCs came from IBM's entry, which destroyed the rents of preexisting sellers of CP/M computers and software.

[34]See Breuhan (1997) for an analysis of the transition from Microsoft DOS to Microsoft Windows as an example of vertical competition that freed customers from their lock-in to applications programs.

Second, PC customers are quite accepting of products rushed into the market. Personal computers are overwhelmingly used for applications that are not mission critical, a fact that removes much of the risk of system crashes. Customers will use partially tested and buggy new systems to gain access to new features or new performance. Researches show that successful software companies forgo quality to speed the time it takes to get the product to market.[35] Beta testing, once a long and carefully contracted process that linked a few lead customers to a vendor, is now a marketing tool, a way to get software in the hands of customers. Speed is king, in large part because customers tolerate change that would be "too fast" in other environments.

Vertical disintegration and divided technical leadership permit very rapid technical progress. Experts push each technology. Divided technical leadership that becomes vertical competition not only permits speed, it also forces a wide variety of competitive races. Enough desire for speed, in turn, demands specialization. Firms cannot master all the distinct technologies they need to bring new platforms, new standards, and so forth to market quickly. Thus speed and disintegration feed back to one another. As a result, for all the competitiveness of its structure, the PC business has had little difficulty in providing economic incentives for technical progress. If anything, the transition to a more competitive structure, notably a vertically competitive one, has led to a transition to an even faster pace of technical progress.

NEW SOURCES OF U.S. ADVANTAGE IN THE NEW SEGMENTS

The technical and personal computing segments of the American industry quickly dominated worldwide competition, but their sources of competitive advantage were different from those that applied in the mainframe computer age. Venture capital played a major role in supporting the entrepreneurial firms' entry and growth in both mini- and microcomputing, while universities played a new role as sources of scientific knowledge and entrepreneurship. Only Cambridge in the United Kingdom has played a role in Europe similar to, albeit weaker than, that played by M.I.T. for minicomputers and by Stanford and the University of Texas for microcomputers and workstations. Industry-specific government policies did not play a major role, while more general policies favoring education and skill development helped market development.

In PCs, the presence of strong complementarities and local knowledge externalities gave major international advantages to the United States or, more precisely, to Silicon Valley, where several firms were at the frontier in each market layer. Intense formal and informal communication and highly mobile personnel, together with the high entry and growth rates already present, exposed these firms early on to new experiments, knowledge, and technologies. These external econo-

[35] See Barr and Tessler (1997).

mies gave American firms major innovative advantages over competitors located elsewhere in the world.

In Europe few new mini- or microcomputer firms entered the industry, for several reasons. In both segments, American producers had first-mover advantage and rapidly took over the European market. Only limited spin-off from European universities took place, while badly developed venture capital markets limited financial support for new ventures. The protectionist measures, such as public procurement, that European governments used for mainframes could not be extended to the new markets.

In Japan the PC industry was focused on the local market; in a time of worldwide standards this local focus resulted in a fragmented market specific to Japanese needs. As a result, Japanese PC hardware exports were small, and PC software exports were near zero. The Japanese industry was thus unable to participate in the worldwide scale economies and substantial external economies associated with microcomputers. As a result, both European and Japanese suppliers were largely irrelevant in the world minicomputer and PC markets. The exceptions to these general observations serve mostly to underscore the analytical lessons. UK start-ups have had some success in niche hardware markets (handheld computers, for example) but have not been effective competitors in worldwide markets.

NETWORKED COMPUTING AND CONVERGENCE

The structure of the overall computer industry has changed dramatically in the 1990s. The segments that had once been separate are converging, bringing firms that were once separate U.S. successes into competition with each other. Fueled by advances in computer networking, convergence has permitted networks of personal computers and workstations to compete with minicomputers and mainframes.[36] Convergence has also enabled vertical competition between sellers in the previously separate segments, as their products are linked together in the same networks. Firms and technologies from personal computing now supply "clients," which are networked to products and technologies from organizational computing, now called "servers." Finally, convergence has led to the development of new technologies and new applications, so it has created important entry opportunities. All three of these changes are competitive, and all have led to reallocations of producer rents.

An important source of demand for networked computing in the early 1990s was as a new technology in organizational computing. Much of this involved replacing mainframes or commercial minicomputers with servers from technical computing. Organizational computing users, however, wanted their separate computing systems linked and also wanted to retain the positive features of personal computing, such as ease of use, and organizational computing, such as power and

[36]See Bresnahan and Greenstein (1995a) for an analysis of this horizontal competition.

the embodiment of business rules and procedures in computer systems. Accordingly, networked computing used hardware and software technologies from personal and organizational computing as complements.

Networked computer systems are highly complex and rich in opportunities in all their various components and dimensions. No single firm could innovate in all parts and subsystems. As a result, network computing has attracted a flood of new specialized entrants: these include technology-based spin-offs from established computer firms, science-based firms established by university scientists, and new firms with market or commercialization competencies. Consider Sun Microsystems, a strong workstation firm that has been a leader in converting workstations, a tool for engineers, into servers. In the process Sun is making a serious attempt to be a standard-setter in commercial computing. The point is that the entry wave in networked commercial computing in the 1990s is stunning in both the variety of sources of entrants and in the variety of offerings the entrants bring to the table.

Networked computing has also led to the very rapid growth of another class of computer applications, *interorganizational computing*. This includes electronic commerce, management of supply chains, electronic data interchange, and a host of other technologies and markets. Interorganizational computing is not new. Yet the opportunities for developing new interorganizational computing applications that stem from use of Internet and other networking technologies are substantial. At this writing, there is tremendous uncertainty about the nature of applications in interorganizational computing. Networked computing is changing rapidly, and it is changing in an unpredictable, constantly evolving direction.

Competition in Networked Computing

The divided technical leadership of networked computing, the uncertainty about invention in it and co-invention in interorganizational computing, and the likely large size of these new segments are a recipe for vertical competition. The rents associated with the control of future standards and technologies will be large, so there is a very large return to moving to control them now.

A stable market structure for networked computing has not yet emerged. Connectivity and compatibility have led to vertically disintegrated supply. Technical change is following a variety of directions with a rise in the number of potential technologies associated with the relevant platforms. Interdependencies and network externalities have increased. New entrants have pioneered many of these technologies. Firms are heterogeneous in terms of size and specialization, activity in various platform components, strategies, and modes of commercialization.

In 1998, neither the dominant design for a network of computers nor for a computer company in this environment is clear. Much of this lack of clarity stems, as it did in the past, from difficulties in forecasting the highly valuable uses of networked computing. Vertical competition seems certain to be a permanent feature of this platform, but the relative strengths of client-based and server-based strategies are highly uncertain. The continued rents of suppliers depend on the emerging structure of the computer industry. There will be technologies whose sellers earn rents and forms of organization of computer companies that deliver rents as well. Because of the competitive disruptions of the 1990s, however, the old rent-generating structures and technologies are threatened, and their replacements are not yet obvious. The market will now select from a wide variety of technological, company and industry structure, and commercialization initiatives. Because the uncertainty about the direction of technical progress is so large, it would be unwise for any particular firm to give up simply because it is behind in the race. Accordingly, a large variety of interesting racing initiatives are taking place throughout networked computing.

One of the more interesting races is for control of network interfaces. Those firms with strong positions on the server end of the business, such as Sun, Oracle, and IBM, have attempted various strategies to extend their control over clients, such as NC and Java, or to render them less influential. Microsoft, the firm with a strong position on the client side has defended itself against all comers, such as Browser, Java, and NC, while attempting to extend its control into the server side. As a result of all this maneuvering, there is widespread speculation that one or a few of the firms controlling key interfaces for connecting modular products will come to dominate networked computing, but no single firm has so far been able to govern change and coordinate platform standards. Clearly vertical integration will increase in the next few years, but substantial vertical competition will also continue. Thus the emergence of a new networked computing platform makes it possible for the U.S.-based firms to strike out for new rents, by innovating to compete for them. It by no means guarantees a position for any firm.

These standards races are struggles not only between distinct firms but also between distinct technologies. As a result, the technological basis of the future computer industry is difficult to forecast. Although this uncertainty makes it hard to predict which *firms* will earn the rents from networked computing, there is little doubt about which *country* will. Almost all the major initiatives to control the new industry rents are based in the United States.

Invention Incentives

Whether competition has changed the computer industry's R&D incentives is a question that cannot be answered quantitatively, for two distinct reasons. First, the boundary between R&D and other activities in the industry is very difficult to draw and thus to measure. The second reason is the dramatic increase in market opportunity facing the industry. The market size for stand-alone computers grew shockingly rapidly in the 1980s, as the personal computer became a far more successful product than anticipated. The market size for networked computing is doing the same in the 1990s, as the Internet is far more valuable as a commercial technology than anyone had anticipated. As a result the total amount of invention is rocketing upward, but it is very hard to determine how much should be attributed to demand-pull and how much to changes in supply, such as competition. Of course, in the long run supply, by opening up the new markets, has unleashed the demand forces. It still remains difficult to say what fraction of the increase in total invention should be attributed to competitive forces.

That portion must be considerable, however. Although the events of the 1990s have removed a great deal of monopoly power from the computer industry, they have not destroyed the return to innovation. Far from it. Now racing against competitors is the incentive to innovate, and it is a powerful and effective mechanism. The vast majority of computer industry competition is technological competition. Price competition might have destroyed the return to innovation; competition whose mechanism is constant racing to gain the next monopoly does not.

U.S. ADVANTAGE LIKELY TO CONTINUE

The uncertainties of networked computing notwithstanding, the United States seems likely to continue to dominate the worldwide computer industry. As computer hardware components and then entire systems became more and more divorced from the rent-generating software such as operating systems, it also became eligible for production at the worldwide cost-minimizing location. Accordingly, there has been a major reallocation of the industry's production of hardware—devices, components, and systems—out of the United States, notably to Asia. This has not posed a challenge to the continued dominance of the rent-generating segments within the United States.[37]

Many governments, notably in Europe, look at networked computing as being about the convergence of computing and telecommunications. Moreover, they are attracted to the idea of a top-down telecommunications-style regulation to direct the rents to their own national champions. This strategy will have some advantages, such as inducing markets to converge to unified and controlled standards more quickly than they would otherwise. In large part U.S. policy is the opposite, including as many alternatives for telephony and computing as possible and waiting for the market to select the winners. Everything in the recent development of computing suggests that the market will ultimately favor the U.S. approach over the European one.

Commercialization will, as always, play a large role in determining the ultimate technological and industry structure. The commercialization mechanisms by which this will occur are not at all clear at this time, as different firms use

[37]See Kraemer and Dedrick (1998) for a fuller treatment of this reallocation.

radically different commercialization strategies.[38] More nearly pure commercialization companies have opened a new international competitive front. Applications software companies for organizational computing, systems integrators, and customs software houses are all worth mentioning here. Many of these firms are American, but there is a healthy international supply in this area.[39] Commercialization, unlike technology, has a strongly local flavor. Many of the important new initiatives serve very specific bodies of customers, specific both to country and to industry. Finally, the uncertainty about applications in a networked environment has meant that there are entry opportunities in this area.

Coming all at once, change in the nature of competition, technologies, and relationships to customers as well as change in firm and industry structure has left traditional management doctrine out of date. Vertical disintegration implies the need to manage alliances, which not many firms know how to do.[40] The transition to effective speedy decision making has also been a difficult one for many companies.[41] There are many other contemporary examples of transition in management doctrine. This will play to the advantage of companies and regions that can experiment and change.

CONCLUSION

Useful business computer systems are complex. They draw upon a wide range of distinct technologies, each of which itself is advancing. Most of the technologies considered "technical"—microprocessors, networking equipment, and systems software, among them—advance rapidly. The less "technical" technologies—the organization of white-collar work and electronic commerce, for example—advance more slowly and are difficult to predict. These very different technologies are in a relationship of innovational complementarity; new kinds of technical capability, such as networked computing, are not much use without invention of new ways of organizing business, new ways of providing service to customers, or other "soft" technologies. The content of the technologies that makes up this system is variegated; microprocessors and advertising are not typically understood in the same way or by the same people. Moreover, seller inno-

[38]Some firms, such as IBM and Oracle, use the bilateral-customer-ties structure for commercialization. Using field sales forces, people-based support structures, and so on, these firms are better with larger customers. Others firms remain close to the PC market model, with only very distant connections to individual customers. This is the marketing and commercialization model of Microsoft, for example, which lacks the organizational capability to engage large customers in bilateral relationships. Like SAP, Peoplesoft, and others, they use commercialization specialists such as systems integration houses, consultants, and custom software firms.

[39]Cap Gemini Sogeti is a successful European systems integrator, while SAP and Baan are successful applications software houses. The service and sales forces of large computer companies, whether U.S. (DEC) or not, are important potential entrants here.

[40]See Eisenhardt and Schoonhoven (1996).

[41]See Brown and Eisenhardt (1997).

vation enables creation of new, but difficult to foresee, applications categories. Users' co-invention then takes time and cleverness. The overall innovation system is, as a result, extremely complex and unpredictable.

This means that market and firm organization are important in computing, especially for commercialization. Seller rents in computing have not gone to those companies or countries with purely technological capabilities. Instead, the sellers who have flourished are those who can align their own technological efforts with market needs and who can take advantage of the leverage implied by users' co-invention. The national institutions and infrastructure that support the development of firms and markets are as important as those supporting technology in explaining U.S. dominance.

A key element of commercialization in all regimes has been the use of the computer platform and associated compatibility standards. Platforms channel seller innovation; backward compatibility means that seller innovation does not outrun user needs. An important result of the use of platforms to organize innovation has been *punctuated equilibrium*. Once a platform standard is in place, technical progress within it tends to be rapid, mutually reinforcing, and focused on immediate market needs. Seller positions tend to be stable. Yet existing platforms do not always serve new needs, as the moves to PCs and networked computing demonstrated. The creation of new platforms is fundamentally disruptive and permits much seller entry. Rents are mobile.

The 1990s have seen three linked changes in computer industry structure and the workings of competition. The process of vertical disintegration, which had been historically confined to making each new market segment less integrated than the last, spread to all the segments. The locus of rent generation shifted downstream to software and applications developments. Computer hardware itself became more of a commodity. Finally, networked computing has brought a very wide list of old and new firms and technologies into a complex web of complementarities and competitive rivalries. Vertical competition appears to have become a permanent feature of the industry.

With all that change, it is natural to ask what has led to the long persistence of U.S. dominance in the industry. Some factors favoring American competitiveness *persisted over time*. First among these is the large size and rapid growth of the American market. Some of the growth is related to the U.S. macroeconomy; the rest is related to education in computer technologies and a highly skilled labor force in information technology. U.S. tax, antitrust, and legal policy has not been supportive of computing, but it has not been dangerously hostile either. U.S. universities, always a source of entrepreneurship, have been highly receptive to the launching of new scientific fields and academic curricula. Finally, there is the tendency for dominant firms and technologies to persist for a long time within the industry's established segments.

Other sources of American competitive advantages have been *changing over time*. In mainframes, for example, the major sources of American advantages were linked to *a single firm's advantages;* IBM presented a unique commitment to R&D policies and to the Chandlerian three-pronged investments in management, production, and marketing. No other firm in the world was able to match IBM's capabilities and investments. In mini- and microcomputers, U.S. advantages were related to *favorable entry and growth conditions* for new firms in new market segments and to the creation of open multifirm platforms that created local knowledge externalities. In computer networks, U.S. advantages are related to the presence of *local knowledge externalities* and strong complementarities between various components of the multifirm standard platform. The creation of each of these new segments involved very substantial entry opportunities for new firms.

Some of these advantages were *transmitted from segment to segment.* For example, the success of venture capital in supporting early computing entrepreneurs as well as other microelectronics and unrelated ventures led to the availability of abundant venture capital in microcomputers and computer networks. Moreover, some of the entrepreneurs important in founding new segments came from established U.S. computer firms. These are weak transmission links. A stronger link was the technologies that network computing drew from established U.S. firms in the already existing segments.

The geographic location of the competencies supporting American success has several times shifted within that large country. In mainframes, American advantages were related to the areas of IBM location of R&D and production, centered in New York but widely dispersed. For minicomputers, the sources of competitive advantage were mainly centered in the eastern part of the United States, with important exceptions such as Hewlett Packard. In microcomputing, and even more so in computer networks, there has been a regional shift from areas in the eastern part of the United States westward toward Silicon Valley. This shift implies the need to consider carefully the unit of analysis of competitive advantages—the division or department, the firm, the region, or the country (Saxenian, 1994). The United States is a large country; as one company or region declined, another grew.

Perhaps the most important advantage, however, has been the flexibility of the U.S. computing industry—its ability to abandon old competencies in favor of new ones. As an example, consider the decline of the centralized vertically integrated large firm in the 1990s. Changing market conditions meant that a new kind of firm was more likely to be successful. With no barriers to exit, the previously highly successful IBM model, not to mention the highly successful IBM, declined. This flexibility and variety has been the hallmark of the U.S. national innovation system. At each critical turn, when large rents were to be earned by an unknown form of computer firm and an unknown technology, the United States has brought forth a wide variety of distinct initiatives. Thus the United States has maintained its leading position not by protecting the old but by seizing the new.

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