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The Evolution of the Digital Computation Industry

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ABSTRACT *All industries are based upon a core of knowledge. Economic evolution is the growth of this knowledge as an experimental and path-dependent process involving markets, firms, finance, entrepreneurship, and often substantial uncertainty. In the set of industries associated with information technology, the core of knowledge is programmable digital computation (PDC). In this paper, we outline the origins and development of PDC, and in particular the path from the mainframe industry to the PC. We tell this story in order to highlight a number of salient features about the relationship between competition and evolution. First, the predominant form of competition was not focused about competitive pricing in existing markets, but rather for the creation of new markets and therefore monopoly positions. Second, as the IBM story demonstrates, this involved leveraging competencies between markets, often deliberately destroying a market in order to create a new one. Third, as the hacker tradition illustrates, much of the entrepreneurial development of the industry came from the users, due to their close conception of the technological possibilities and opportunities. Fourth, we highlight the overarching importance of the setting of standards (by fiat, by self-organization, or by monopoly) and the role this has in reducing uncertainty. We offer some policy and management lessons based upon this analysis.*

Keywords: uncertainty, evolution, computer industry, knowledge.

Introduction

This paper is about the evolution of the programmable digital computation (PDC) industry from the perspective of Schumpeterian competition driving the growth of knowledge. The economic history of PDC is primarily a story about innovation and standards setting in an ongoing process of creative destruction. We emphasize the presence of fundamental uncertainty in the evolution of the technology, and how this uncertainty was key to shaping the sorts of competition that drove the technology forward. We use this to illustrate the evolutionary relationship between competition and technology policy.[1] In this view, economic growth is a product of the growth of knowledge, and the growth of knowledge is a consequence of firms competing by generating and testing novelty in the face of uncertainty.

This paper is set out as follows. We begin with the development of the concepts underlying PDC by mathematicians. In the next section we discuss the first major

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market for PDC in mainframe computers, a story largely associated with the IBM Corporation. Then we follow the explosion of new forms of technologies and industries that spun off from this, paying particular attention to the perception of opportunities and constraints by users and developers of the technologies. Within the next four sections, the first two review the development of the PC industry in the late 1970s and the emergence of the IT industry in the early 1980s, while the later sections address the overriding structural characteristic of vertical disintegration. Some management and policy implications conclude.

Prehistory of Programmable Digital Computation

The exact origins of PDC are somewhat difficult to pin down. Properly, we should trace them through mechanical clock-making and steam engines, for the 'Analytical Engine' that Charles Babbage built in 1833 was indeed a steam-powered mechanical computing machine.[2] But the physical form is not so important as the underlying concept of binary algebraic logic. All of the building blocks of modern computing (code as software, gates and circuits, or an electrical system of relays and switches as hardware) are realizations of binary algebraic logic.

The concept of binary algebraic logic stems from the English logician George Boole, who published in 1854 *An Investigation into the Laws of Thought.* Unfortunately Boole did not much succeed in the object of his inquiry, which is to say that he did not discover the laws of thought. But what he did discover was a system of logical reasoning that, although of limited use in explaining how humans think, furnished the kernel of how computers might think. The answer, of course, is that they think logically, iteratively, recursively and in binary terms. This is Boolean algebra, a branch of set theory devoted to the analysis of systems of objects with two possible states (on–off, open–closed). Binary algebraic logic is how electrical circuits perform computation.

In the 1860s, Charles Sanders Pierce brought the work of George Boole to the USA, and by 1880 he had extended the concepts and applications of Boolean logic by proposing that electrical calculating machines could be constructed using switching circuits to model Boolean logic. In 1940 Claude Shannon showed precisely how electrical circuits were equivalent to expressions in Boolean algebra.

In the 1930s, the English logician Alan Turing sketched the logic of a machine (an automaton) designed to read and follow coded instructions. This is the underlying dynamic component of a programmable computer. In 1945 the first all electronic digital computer was developed under contract from the US Army at the University of Pennsylvania. ENIAC[3] was a special purpose machine hard wired to do computation and a direct descendant of steam powered mechanical adding machines of Babbage's time. By 1951, the first programmable digital computer was developed through collaboration between the developers of the ENIAC and the Remington Rand Corporation to utilize John von Neumann's stored program architecture. The PDC thus emerged, mid-twentieth century, as a product of earlier work on mechanical computing machines, the algebraic logic of thought, electrical circuits, vacuum tubes, and machine readable code.

Mainframes, IBM and IT

During the 1920s through to the 1940s IBM established dominance in the electromechanical punch-card business. This was the market that mainframe computers would move into. In 1952 IBM entered the general-purpose digital computing industry after having been involved with the development of related technologies for 25 years, including producing components for the Mark I computer produced at Harvard in 1944. IBM leveraged its competencies in electromechanical manufacturing, digital computer design and its relationship with large commercial clients (built up through the punch-card business) in order to use its dominance to destroy the old industry and create a new one.

The motive for this was that IBM was already on the competition policy radar. The US Justice Department had earlier initiated anti-trust actions against IBM relating to its practices in the punch-card business, which hastened the transition to computing as its primary business focus.[4] Faced with legal suasion in one market, they moved to another. In 1956, IBM signed a consent decree ending the anti-trust action and also IBM's punch-card business. By the early 1960s IBM had fully transformed itself into the leader in electronic computer technology. (Over two thirds of its revenue came from the sale of mainframe computers, including related peripherals, software and services.) With the demise of the punch-card business, the remaining third of IBM's business consisted of electric typewriters and office equipment.[5]

Thomas Watson (Senior and Junior) drove IBM to dominance through profit maximization. But the IBM story, we think, is not essentially about price competition, but rather about entrepreneurial vision and the ability of key leaders to see what is possible and what is not. A market for computer systems did not then exist, it had to be created. IBM was faced with tremendous uncertainty. Anti-trust action threatened its mechanical punch-card business, and faced with a threat to its primary revenue source the managers bet the company on a business and market that did not then exist: computers. This sort of decision is not management *per se*, but entrepreneurial vision of the connections between capabilities and knowledge within their own firm and new knowledge arising in a market environment, and then combining these elements to create new capabilities and knowledge resulting in new products and markets. Uncertainty appears, then, as the context of entrepreneurial imagination and the spur to innovation in the creation of new products, markets and firms. Uncertainty is the prime feature of the environment of innovation.

The growth of knowledge in the field of electronic circuits advanced at a rapid pace throughout this period. In 1956, John Bardeen, Walter Brattain, and William Shockley shared the Nobel Prize in Physics for their work in developing the transistor at Bell Labs. The transistor represented a major breakthrough, replacing vacuum tubes while using significantly less power and space and with higher reliability. The development and commercialization of the transistor led to the creation of the semiconductor industry. The potential application of semiconductors in many different products led to the rapid growth of a number of new start-up companies. Fairchild, Motorola, Texas Instruments, and RCA were some of the early entrants. Improvements in the underlying technologies drove the development of crucial new devices, particularly Random Access Memories (RAM), and ultimately the Microprocessor (computer on a chip).

Advances in the size and cost of electronic circuits led to the rise of a number of start-up firms, many of which were founded by ex-IBM employees (such as Ken Olson the founder of Digital Equipment Corporation). These used the new advances to create another entirely new product category and market in minicomputers. While the mainframe business remained predominately focused on enterprise-wide computing solutions, the minicomputer market emerged and grew during the 1960s and 1970s by producing smaller systems addressed to the needs of the scientific and engineering communities. The industry evolved in a flux of new technologies, new firms, and new markets. Knowledge grew in an autocatalytic manner, where each new building block set in train a kind of explosion of search and experimentation as connections were made, forming new systems as building blocks for yet further systems, all as a process of cumulative technological evolution.[6]

The growth of the IBM System 360 and the follow-on System 370 engendered a whole category of firms labeled PCMs (Plug Compatible Manufacturers). These companies took advantage of both the size of the IBM market and the fact that they could competitively produce peripheral equipment compatible with IBM systems at a lower price than IBM due to lower R&D and overhead costs. The effect of price competition was a massive expansion in the size of the industry and the market. These companies grew in number and size throughout the 1960s and 1970s, producing tape drives, disk drives and disk packs.[7]

The simple act of taking another firm's product and copying it, with the intention of being able to sell it cheaper than the firm that created the original design, is an act of innovation as knowledge creation. The creation of cheaper replicas of the original product led to improved economic efficiency, but, more importantly, to the disbursement of knowledge and the creation of specialized firms with specialized focus. The effect of the clones was to make possible much greater specialization about the technology.[8] Cloning created a stable environment for further knowledge growth by increasing specialization and the division of labor. Throughout the 1960s and 1970s, developments in the semiconductor, minicomputer and Plug Compatible industries created the technological building blocks that would enable a major change in the computing paradigm. But what was driving this process?

Paradigms, Hobbyists and Hackers

At the request of a Japanese calculator company, Intel started work on the design of the first Microprocessor in 1969. This led to the Intel 4004, and by 1972 Intel had released the 8008, and 8-bit processor, followed by the 8080 in 1974, also an 8-bit processor with addressing capability for 64 K bytes. Soon, similar designs emerged from Zilog, with the Z80, and then from Motorola, with the 6800.[9]

The microprocessor provided the hardware basis for the creation of a desktop microcomputer. This capability was widely noticed and understood by many established firms, but in retrospect was left surprisingly unexploited. Interestingly, the entrepreneurial founder of the minicomputer business and president of DEC, Ken Olson, is reported to have killed a desktop project seeing no conceivable need for a computer in the home.[10] Even Hewlett-Packard turned the opportunity down when Steve Wozniak, co-founder of Apple Computer, then employed by HP, approached them with his initial prototype of what would eventually turn into the Apple I.[11]

This is an example of the operation of knowledge frameworks.[12] HP and Digital did not envision a market for a personal computer, the market did not exist, and it had not been created. Digital and HP did not see the PC as a problem or an opportunity, it did not create uncertainty, it did not fit into their existing knowledge frameworks. The creative capabilities of a firm to do something new, and to take risks with unknown possibility of success, rests fundamentally on recognition of a problem as an opportunity. But the desktop minicomputer was never really seen as an opportunity because it was never seen as a problem. As George Shackle explains, '[t]he expectation-former is provided with no given and ready-made list of relevant sequels to any one of the rival courses open to him. Such sequels are for him to conceive, to invent'.[13]

The development of the first microcomputers was left to hobbyists, many of whom belonged to and religiously attended meetings of local microcomputer clubs, such as the Homebrew Computer Club in Sunnyvale, CA. These clubs were generally comprised of young engineers who were not only fascinated with computers, but frustrated with the bureaucracy and difficulty of working with mainframes in a corporate environment, and longing for a machine of their own to program and experiment with.[14]

The first commercial microcomputer was the MITS/Altair 8800, a basic kit microcomputer. The MITS system came with no software. Anyone buying an early system had to write their own software and enter it through switches on the front panel. Two young programmers saw the original ads for the MITS system in *Popular Electronics* and worked to adopt a version of the BASIC programming language they had written to run on the MITS machine, with the intention of selling their version of BASIC to MITS. With this, Paul Allen and Bill Gates' Micro-Soft (later changed to Microsoft) completed its first deal. Gates and Allen became software developers through the 'hacker' tradition as masters of electronic mischief. Both had worked in Seattle for a local company uncovering bugs in DEC operating systems by finding ways to crash the operating system.

The roots and antecedents of an entirely new market structure emerged spontaneously, and not as the result of rational agents engaging in price discovery through market competition. Young talented engineers and 'masters of electronic mischief', all frustrated with the stifling bureaucracy within existing economic organizations that prevented them from pursuing their curiosities, spontaneously came together in informal organizations. Hackers experimented in their garages with new designs and anyone coming up with a reasonable design was eager to share it with their friends at the next computer club meeting. One person would create a basic hardware design, another contributing software to run on the system, another created a new add-on circuit board. This sort of cooperative interaction led to the ever-expanding capabilities of these primitive systems. This process represents the antecedents of the personal computer industry, technological innovation originating within the user community establishing the basic open architecture framework that would ultimately come to reshape the entire information technology industry.[15]

Although hobbyists had been buying microcomputers for several years, and a number of companies had created a primitive market for the personal computer, critical mass for the personal computer was not reached until 1977 with the introduction of the Apple II, the Tandy TRS 80, and the Commodore PET. Without these product introductions, the expansion of the retail channel with Computer-Land, and the development of application software, the microcomputer would have remained essentially defined by its hobbyist roots. The key point is that all of these activities were created out of the hobbyist movement, a cooperative social structure that led to the emergence and co-evolution of both the supply and demand side characteristics of an entirely new market.

The Beginning of the Personal Computer Industry

Steve Jobs and Steve Wozniak, an active member of the Homebrew Computer Club, were high school friends in Cupertino, CA. The two provided the entrepreneurial spirit behind the founding of Apple Computer.[16] These unique, raw capabilities would propel Apple far beyond any firms of the hobbyist period.

Steve Jobs had no business education and little experience, but did recognize that if Apple were to grow it would need capital. Jobs, having worked at Atari, knew Nolan Bushnell, the entrepreneurial founder of Atari. Jobs approached Bushnell for advice about where he should turn for more capital. Bushnell gave Jobs a brief tutorial on the venture capital world and provided him with the name of Don Valentine, the founder and general partner of one of the best known Silicon Valley venture capital firms. Valentine's encounter with Jobs would prove to be critical in Apple's ability to move beyond the hobbyist phase and become a serious microcomputer business. Valentine said he was not prepared to invest in a company that had no marketing capability. Valentine suggested Jobs contact Mike Marcula, an experienced semiconductor senior marketing manager who worked for Valentine at Fairchild. Markula offered to underwrite a $250,000 investment in Apple in return for a one-third share of the business. He immediately hired a professional management team from around Silicon Valley and securing venture funding from Valentine, Andy Grove and Arthur Rock of Venrock Capital who became Apple's first Chairman.[17] The beginnings of the PC industry were as much about financial and managerial competencies as about the underlying product technology.

The IBM PC

While Apple can be credited with starting the personal computer revolution, IBM must be given the distinction as being responsible for unleashing the upheaval that would lead to the overthrow of the old mainframe paradigm and the complete restructuring of the IT industry. By the end of the 1970s IBM's share of the global computer market had dropped to 40%, from its peak of 70% in the 1960s. IBM had failed to anticipate the rise of the minicomputer; plug compatible clones continued to eat at IBM's business, and the US Justice Department had been pursuing anti-trust actions against IBM for 13 years.

Interest in producing a small computer at IBM was not new; in fact IBM had a program in the mid-1970s to produce just such a system, the results of the program were disappointing. In August of 1980 William Lowe, a lab director in IBM's Entry Level Systems group in Boca Raton, FL, was given the go ahead on Project Chess—development of a microcomputer. Months later the Corporate Management Committee at IBM, under John Opel's leadership, established the PC project. Opel was personally committed to seeing that IBM would be successful in filling what he perceived to be a hole at the low end of IBM's product offering. Opel made it clear that the group in Boca could have whatever they needed and, on Opel's authority, could break the established rules of business within IBM.[18]

IBM had witnessed Apple's success, while firmly believing that Apple was vulnerable and incapable of tapping the business market. IBM felt that market entry timing was critical. As a result the PC group chose to break with tradition and source major components for the IBM PC from external suppliers, choosing Intel to supply the Microprocessor and an unknown company by the name of Microsoft to provide the Operating System. In addition to the open architecture decision, the PC group also determined that the PC should not be marketed through IBM's traditional internal sales organization. The IBM sales organization was structured around selling big systems, they operated on an incentive system that would not have encouraged the selling of microcomputers.[19]

IBM introduced its PC in 1981. The IBM name and reputation immediately attracted large and small companies alike, many of whom had previously hesitated buying and using the personal computer. By 1983 IBM's presence had led to significant growth in the global PC market.[20] At the time the IBM PC clone market was just beginning to develop, no one knew or understood the significance of the gale of creative destruction that had been unleashed, ultimately leading to the complete reordering of the IT industry. IBM's development of an open architecture PC, with many components outsourced, resulted in IBM losing its dominant position within the IT industry. In the process IBM created the WINTEL (Microsoft Windows and Intel) dynasty and a horizontally disintegrated PC industry structure.[21] The PC revolution was well underway, laying the foundation for a rapid increase in technology diffusion through out the economy leading to productivity improvements and economic growth.

The history of the IT industry certainly is a wonderful vision of the evolution of an autocatalytic knowledge set, catalyzed by the actions of a diverse set of agents, driven by a diverse set of motives, all resulting in an explosion of economic activity and an avalanche of creation and destruction.[22] The heart of this process of creative destruction is the epistemic cycle of uncertainty, imagination and innovation.

From Vertical Integration to Horizontal Disintegration

IBM and the other leading firms in the IT industry during the mainframe era were vertically integrated enterprises. Computer technology had just emerged prior to the end of WWII; there was no network of firms capable of providing the various pieces of a large computer system. In this situation, the fact that the firms in the IT industry were vertically integrated was not a matter of choice but of necessity, they had to create the knowledge and the elements necessary for producing and delivering computer systems, just as they had to create the market for these systems.[23] The growth of the industry led to increased knowledge, as well as opportunities for economies of scale and competence. As a result there was an explosion in the number of firms within the IT industry during the 1960s and 1970s, including semiconductor firms, storage technology firms, application software firms, and suchlike. The growth of new specialized firms provided the capabilities necessary to support the emergence of the horizontally disintegrated PC paradigm and the corresponding explosion in IT industry growth. This is a wonderful example not only of the division of labor depending upon the extent of the market, but also of the division of knowledge.[24]

As the market grows and matures, knowledge becomes dispersed and specialization and economies of scale lead to increased innovation and growth of the market through the horizontal disintegration of the industry structure. Vertical integration gives way to horizontal disintegration and ushers forth an increased rate of technical innovation and economic activity.

The Disintegrated Horizontal PC Structure

Understanding the dominance of the horizontally disintegrated PC structure lies in one of the most basic concepts of economics, Adam Smith's principle of the division of labor leading to specialization. The key to Smith's theory, as pointed out by Loasby, is in the ability of the division of labor to 'create increased, and also novel, specialist competencies'.[25] In this view, the power of the division of labor is in its essence a theory of knowledge creation.[26]

Through specialization, firms are able to increase their rate of learning. With the firm's entire attention focused on one particular technology area they are able to find creatively simple ways of extending the existing technology with relatively minor modifications to designs and manufacturing processes. These extensions can be quickly adopted and commercialized because they rely on existing technical know-how that is re-combined and not on wholly new inventions. New and creative ways of using existing technologies have led to the vast majority of innovations that spurred the growth of the PC industry over the last 20 years.

The level of specialization, or modularity, in the IT industry today is well advanced. Every major component that goes into making up a computer system is comprised of a separate group of firms, an industry to themselves, within the overall IT cluster—microprocessors, memories, graphics chips, communication boards, monitors, floppy disk drives, CD-ROMS, hard disk drives, tape drives, software applications, and even services. Within a horizontally disintegrated system, like that of the PC, coordination becomes critical to the success of the system. Coordination in this sense means the establishment of standards across the entire network of firms that ensure compatibility between all of the modular components that go into making the complete system.

Within the PC industrial cluster the dominance of Microsoft and Intel has ensured an orderly and efficient standards setting process, namely they set the standards. While not strictly competitive in the sense of a coordination game among equal players, it is an effective solution that provides the necessary order to underpin the spectacular growth rate of the PC industry. The order provided by standards provides a framework that enables and encourages the creation of new innovations that benefit the entire system.

The source of Microsoft and Intel's dominance has its roots in IBM's decision to pursue an open systems approach in bringing its PC to market, and as a result outsourcing the operating system and microprocessor. As discussed previously, IBM's decision to create an open architecture for the PC was driven by its desire to get to market quickly. The decision completely went against the culture and tradition of vertical integration within IBM. Two important points need to be made. First, IBM had the opportunity to pursue outside capabilities in putting together the PC; the requisite competencies existed in the market place, and had in fact arisen and developed within the mainframe paradigm. Second, within IBM, a company that was the dominate firm within the IT industry for 30 years, there were those capable of breaking the IBM paradigm and going outside to source major components for the PC. The decision to source externally is responsible for IBM ceding dominance in the IT industry to Microsoft and Intel, but at the same time may be responsible for IBM continuing to be one of the largest and most successful firms within the IT industry today.

The Failure of Established Firms

Many of IBM's vertically integrated fellow travelers from the mainframe and minicomputer era are no longer around. Famous names from the past like Sperry-Univac, Control Data, Burroughs, Wang, Data General, Digital Equipment, and so forth, have been replaced by a long list of billion dollar firms that did not exist until the PC era, many of which represent the fastest growing firms in the history of the United States (e.g. Apple, Compaq, Dell, Seagate, Quantum, Cisco, Oracle, EMC). How do we explain and understand this massive failure of established firms to manage the transition from the mainframe era to the PC era?

Understanding the paradigmatic nature of knowledge frameworks within firms[27] is critical to understanding how once successful, established firms, whither and die in the face of shifts in the competitive dynamics within an industry. Paradigms are a source of both strength and weakness[28]—strength in that they tend to reinforce successful patterns of behavior, and weakness for the same reason. Andy Grove has this to say:

> Senior managers got to where they are by having been good at what they do. And over time they have learned to lead with their strengths. So it's not surprising that they will keep implementing the same strategic and tactical moves that worked for them during the course of their careers—especially during their 'championship seasons'. I call this phenomenon the inertia of success. It is extremely dangerous . . . When the environment changes in such a way as to render the old skills and strengths less relevant, we almost instinctively cling to our past.[29]

To understand how paradigms lead to the downfall of successful firms we will draw on the concept of self-organization. Self-organization is the process whereby competitive and cooperative interactions between individual agents, within industries and clusters of industries, leads to the establishment of structural relationships governed by a set of endogenously generated rules. These rules and relationships establish the competitive environment and the boundaries of interactions. Firms constantly seek to adapt their competencies to the environment they help create. Those firms that are successful in adapting succeed, and those that do not are selected against. But when an entirely different set of relationships and rules emerge from within the existing industrial cluster many firms become hopelessly confused, either failing to recognize the significance of the emerging changes, or in fact denying that anything is really changing. Just how dramatically different the rules of the game were in the mainframe era from those of the PC era has been outlined by Moschella[30] and is summarized below.

- *From systems-centric to PC-centric.* Beginning in the 1980s most of the development energy within the IT industry became focused on the growth of the PC. Later even larger computer systems began to be redesigned around a modular model, resulting from the shift to a client/server model from a data center model of data processing.
- *From corporate to individual computing.* In the 1960s and 1970s IT emphasis was on corporate efficiency through centrally controlled and administered data processing. With the PC era, the focus shifted to individual and work group productivity. As a result computers moved out of the domain of the specialized data processing professional and into the domain of white-collar workers. With this, the IT purchasing decision in many corporate environments became decentralized as well.
- *From Grosch's law to Moore's law.* Grosch's law states that computer power increases as the square of the cost, a computer that was twice as expensive should have four

times the processing power. This was the argument that favored the implementation of large systems during the 1960s and 1970s. Moore's law stated that semiconductor performance would double every 18–24 months for the foreseeable future. Moore's law led to the PC, and ultimately high performance network and enterprise servers of modular design to soon surpass mainframes in terms of price performance.

- *From proprietary to commodity systems.* The mainframe era was characterized by proprietary systems, presenting users with high vendor switching costs. Since all IBM-compatible PCs run the same operating systems and software, PC switching costs are close to zero.
- *Direct versus indirect selling.* Virtually all mainframe sales, and a significant portion of minicomputer sales, were coordinated through direct sales channels in line with a high system-selling price. PC sales, due to the relatively low selling price, are managed overwhelmingly through indirect channels; predominately retail stores and dealers today.
- *From a vertical to a horizontal supplier model.* All of the above combined to redefine the very nature of what a computer company was. The major mainframe and minicomputer companies were large vertically integrated companies, selling highly proprietary systems with long sales cycles and high prices. The PC companies are predominately screwdriver assembly operations, accumulating components from specialized manufacturers, and selling low cost systems based upon brand and channel differentiation.

The significance of the shift in paradigm between the mainframe and the PC era was such that many of the competencies developed and sharpened within the mainframe paradigm were poorly adapted to the competitive environment of the PC era. Little wonder that so few firms from the mainframe era survived to be successful in the PC era. Only a small handful of established firms from the mainframe era were able to shed past knowledge and acquire the knowledge necessary to succeed in the new paradigm.

Christensen and Bower[31] have argued that established customers play a critical role in the process of firms maintaining a death grip on old knowledge—customers reinforce firm paradigms. Certainly the mainframe companies were listening to data processing professionals, while the early buyers and adopters of PCs were to be found within the user communities. Within many companies the data processing professionals were as strongly in denial about the future of the PC as the mainframe firms themselves. PCs were first introduced into many corporate environments through the user community, not through the data processing department. Therefore the mainframe suppliers would continue to hear what they wanted to hear from their customers, the data processing professionals. All the while the PC revolution gained momentum among the user communities.

> Our conclusion is that a primary reason why such firms lose their positions of industry leadership when faced with certain types of technological change has little to do with the technology itself—with its degree of newness or difficulty, relative to the skills and experience of the firm. Rather, they fail because they listen too carefully to their customers—and customers place stringent limits on the strategies firms can and cannot pursue.[32]

On the supply side, Henderson and Clark[33] argue that the failure of established firms resides in the difference between radical and incremental innovations.

Incremental innovations build upon improvements in the individual components within an established architectural framework. Radical innovations are associated with a complete change in the architectural framework. They write:

> Incremental innovation tends to reinforce the competitive positions of established firms, since it builds on their core competencies or is 'competence enhancing' . . . In contrast, radical innovation creates unmistakable challenges for established firms, since it destroys the usefulness of their existing capabilities. In our terms, it destroys the usefulness of both architectural and component knowledge.[34]

The above two arguments are not substitutes, but complements. Both reinforce our central thesis that economic growth is an outcome of the growth of knowledge, and the growth of knowledge is an evolutionary process involving adaptation, the generation and testing of novelty and imaginative actions in the face of uncertainty. The question now is what can be done to promote it?

Conclusion—Management and Policy Implications

Today, as the information technology industry continues to evolve from the PC paradigm to the network centric paradigm new challenges for industry, management and public policy are emerging. Features of this new paradigm, discussed in detail in Mandeville,[35] Hearn *et al.*,[36] and Moschella,[37] can be briefly summarized here as follows.

- *From microprocessor to communications bandwidth.* Today the drivers of improvement in ICTs are changing dramatically. As many more people begin to use the Internet, the limiter is not processor speed but network bandwidth and content.
- *From Moore's law to Metcalfe's law.* The economics of networks are replacing the economics of silicon. Metcalfe's law states that the cost of a network increases linearly as it expands, while the value of the network increases exponentially.
- *From a horizontal computer industry to a converged industry value chain.* The process of convergence of a number of previously separate industries is leading to significant structural changes in these industries—computers, telecommunications, consumer electronics and media.
- *From innovation in manufacturing to innovation in services.* With new service products and processes based on ICT platforms, the bulk of the economy is beginning to resemble the ICT sector in terms of the furious pace of innovation.

But what lessons does our story offer currently for industry/management generally and innovation/communications public policy in particular? We consider four.

First, this is a story of new products for new markets championed in each instance by respective clusters of new start-up firms. This process is well illustrated by semiconductors, minicomputers, hard disk drive producers, PCs and IBM itself. We saw that while IBM created the mainframe, it completely missed the opportunity represented by the minicomputer. But some within IBM did see these new possibilities, and established new firms for their realization. Still, IBM later on was one of the few mainframe firms to successfully make the transition from the mainframe era to the PC era. It did this by firstly establishing an independent business unit to champion the IBM PC, and subsequently by reinventing and transforming itself for the new era.

A lesson for management and policy is that new activities are best carried out by new organizations.[38] This reflects Arrow's basic point regarding the economic characteristics of information, that information costs are not uniform in different directions.[39] Information channels which enable agents to send and receive signals within their environment are costly to establish and maintain. But once established it is less expensive to use an existing channel than open a new one. Thus it will be difficult to reverse an initial commitment in the direction in which information is gathered.

Established firms rely on existing information channels, they listen to their customers and often neglect to explore new information channels that would expose new ideas and opportunities. This can be fatal, particularly at critical inflexion points where the prevailing industrial paradigm shifts. But new organizations at the outset create appropriate information channels for new activities in the process of adopting appropriate new competencies. They don't have to unlearn old competencies or disinvest in old information channels. These issues become especially critical in the case of radical innovation such as the PC.

Public policy can assist this process by ensuring that appropriate social elements—such as venture capital availability, incubators, and an entrepreneurial culture—are in place to facilitate new startups. Again, these aspects are more crucial at inflection points.

Second, the US computer industry clearly illustrates that innovation is a social process involving the cumulative growth of knowledge from many sources, including copycat firms. An innovative industry progresses rapidly when information essential to innovation flows fairly freely between firms.

Thus management and industry practices familiar to players in Silicon Valley, such as industry networking, strategic alliances and other forms of cooperative interaction are now becoming more commonplace throughout industry in the new economy. These developments have clear long-term implications for national and international IP regimes—generally weak IP rights facilitate innovation, strong IP rights block it.[40]

This cumulative, social knowledge-creation process of innovation relies on variety, diversity, experimentation and associated failure as a feedback learning process and the role of capital markets as an experimental laboratory.[41] These are the phases when markets, and not just firms, are called upon to do their hardest work. By implication this presents the policy window when external agents can most strongly affect development of the industry. The market eventually defines the essential features of any future successful new products, and, in so doing, it defines the essential capabilities for the emergence of new paradigms. In essence, the market provides the workspace to test the efficiency of new knowledge. This is why markets are important for growth. Uncertainty and discontinuous change are also part and parcel of the innovative process in rapidly changing environments. Innovation policy needs to understand these basic big-picture evolutionary features of the innovation process, and this needs to be informed by the evolutionary perspective rather than the conventional economic perspective.[42]

Third, the PC era illustrates the crucial role of standards in industry coordination. The standards setting role of Microsoft and Intel suggest that monopolies can sometimes have beneficial impacts. In situations where industry standards don't emerge spontaneously, public policy may play a role to help facilitate their emergence.

Finally, our story illustrates the relative importance of dynamic efficiency versus static efficiency in innovative industries. Dynamic efficiency is about creativity, adaptive potential, whereas static efficiency is about control, order, company policy and procedures, and how to economize on scarce resources. Obviously, both forms of efficiency are needed. For example, some stability is required to allow innovation to take place. But it would be fair to say that policy makers and management tend to generally be biased toward the static efficiency mindset. Arrow[43] argues that the pursuit of efficiency may lead to rigidity and unresponsiveness to further change, while Schumpeter[44] argues that over the long run, a degree of static inefficiency may improve overall performance.

Notes and References

1. See M. Beardsell and J. V. Henderson, 'Spatial evolution of the computer industry in the USA', *European Economic Review*, 43, 1999, pp. 431–56; R. Baptista and P. Swann, 'A comparison of clustering dynamics in the US and UK computer industries', *Journal of Evolutionary Economics*, 9, 1999, pp. 373–400; F. Malerba, *et al.*, 'Competition and industrial policies in a history friendly model of the evolution of the computer industry', *International Journal of Industrial Organization*, 19, 2001, pp. 635–64. M. Waltrop, *The Dream Machine: JCR Licklider and the Revolution that made Personal Computing*, Viking, New York, 2001, provides an excellent account that focuses on the development of parallel computing.
2. Yet, the mechanism intention was very similar to that of modern day computers, 'Babbage intended that the machine free people from the more boring aspects of thinking, just as some of the new machines of that era were freeing people from physical drudgery', P. Freiberger and M. Swaine, *Fire in the Valley*, Osborne/McGraw Hill, Berkeley, 1984, pp. 3–4.
3. The June 1946 edition of *Popular Mechanics* has a story on page 139, opposite a story about the invention of a new paddling-pool toy, about ENIAC (Electronic Numerical Integrator and Computer) with pictures showing a 'rear view section of machine showing tubes, plug-in chassis and transformers'. The story is headed 'It thinks with electrons' and describes how it will be very good at solving mathematical problems. There was, it seemed, no telling quite what this thing was.
4. J. Chopsky and T. Leonsis, *Blue Magic: The People, Power and Politics Behind the IBM Personal Computer*, Facts On File, Inc., New York, 1988, p. 4.
5. A. D. Chandler, Jr, 'The computer industry: the first half-century', in D. B. Yoffie (ed.), *Competing in the Age of Digital Convergence*, Harvard Business School, Boston, 1997, p. 41.
6. J. Potts, *The New Evolutionary Microeconomics: Complexity, Competence and Adaptive Behaviour*, Edward Elgar, Cheltenham, UK and Northampton, MA, USA, 2000, pp. 68–70.
7. Chandler, *op. cit.*, p. 59.
8. This sort of dynamic is also evident in nature where such behaviors as mimicry represent an emergent phenomenon in complex adaptive systems. See J. H. Holland, *Hidden Order: How Adaptation Builds Complexity*, Perseus Books, Cambridge, MA, 1995, p. 28.
9. R. N. Langlois, 'External economics and economic progress: the case of the microcomputer industry', *Business History Review*, 66, 1992, p. 9.
10. Freiberger and Swaine, *op. cit.*, p. 20.
11. M. Moritz, *The Little Kingdom: The Private Story of Apple Computer*, William Morrow and Company, Inc., New York, 1984, p. 126.
12. See Y. B. Choi, *Paradigms and Conventions: Uncertainty, Decision Making and Entrepreneurship*, University of Michigan Press, Ann Arbor, 1993; and B. J. Loasby, *Knowledge, Institutions and Evolution in Economics*, Routledge, London, 1999.

13. G. L. S. Shackle, *Epistemics and Economics: A Critique of Economic Doctrines*, Cambridge University Press, Cambridge, 1972.
14. R. X. Cringely, *Accidental Empires*, Penguin Books, London, 1996, suggests, more or less, that much of the motive driving the technological development here stemmed from nothing more complex than young male club members striving to impress each other with what they could make their machines do.
15. See G. Buenstorf, *Designing Clunkers: Demand-Side Innovation and the Early History of the Mountain Bike*, Max Planck Institute for Research into Economic Systems, Evolutionary Economics Unit, 2001, for a similar account of the user lead evolution of the mountain bike industry.
16. Langlois, *op. cit.*, p. 15; Moritz, *op. cit.*, p. 122.
17. See *Ibid.*
18. Chopsky and Leonis, *op. cit.*, p. 27.
19. *Ibid*, pp. 20–4.
20. D. C. Moschella, *Waves of Power: The Dynamics of Global Technology Leadership 1964–2010*, AMACOM, New York, 1997, p. 10.
21. *Ibid*, p. 32.
22. J. A. Schumpeter, *Capitalism, Socialism and Democracy*, Harper Perennial, New York, (1942) 1975.
23. See P. Robertson, 'Competencies, transaction costs and competitive strategy', in N. J. Foss and C. Knudsen (eds), *Towards a Competence Theory of the Firm*, Routledge, London, 1996, pp. 75–96.
24. J. Potts, 'Knowledge and markets', *Journal of Evolutionary Economics*, II, 2001, pp. 1–19.
25. B. J. Loasby, 'The concept of capabilities', in N. J. Foss and B. J. Loasby (eds), *Economic Organization, Capabilities and Coordination: Essays in Honour of G.B. Richardson*, Routledge, London, 1998.
26. Potts, *op. cit.*, 2001.
27. Choi, *op. cit.*; Loasby, *op. cit.*, 1999.
28. Choi, *op. cit.*; J. E. Harrington, Jr, 'Rigidity of social systems', *Journal of Political Economy*, 107, 1999, 40–64.
29. A. S. Grove, *Only the Paranoid Survive*, Currency/Doubleday, New York, 1996, p. 127.
30. Moschella, *op. cit.*, pp. 14–16.
31. C. M. Christensen and J. L. Bower, 'Customer power, strategic investment, and the failure of leading firms', *Strategic Management Journal*, 17, 1996, pp. 197–218.
32. *Ibid*, p. 198.
33. R. M. Henderson and K. B. Clark, 'Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms', *Administration Quarterly*, 35, 1990, pp. 9–30.
34. *Ibid*, p. 13.
35. T. Mandeville, 'Measuring up in the new economy', *Australian Financial Review*, 17–November 2000, pp. 4–5.
36. G. Hearn, T. Mandeville and D. Anthony, *The Communications Superhighway: Social and Economic Change in the Digital Age*, Allen & Unwin, St. Leonards, New South Wales, 1998.
37. Moschella, *op. cit.*
38. Hearn *et al.*, *op. cit.*, p. 82.
39. K. Arrow, *The Limits of Organization*, W.W. Narton &Co., New York, 1974.
40. T. Mandeville, *Understanding Novelty*, Ablex Publishing Corp., Norwood, NJ, 1996.
41. Potts, *op. cit.*, 2001.
42. D. Rooney, G. Hearn, T. Mandeville and R. Joseph, *Public Policy in the Knowledge Economy*, Edward Elgar, Cheltenham, UK and Northampton, MA, USA, 2002.
43. Arrow, *op. cit.*, p. 49.
44. J. A. Schumpeter, *Capitalism, Socialism and Democracy*, 3rd edition, Harper and Brother, 1950, p. 83.