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IBM and its Imitators: Organizational Capabilities and the Emergence of the International Computer Industry

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In this paper I will examine the utility of the theory of organizational capabilities and evolutionary economic change, as conceptualized by Richard Nelson and Sidney Winter, for explaining the emergence of the computer industry. In particular, I will discuss whether this theory fits the historical experience of IBM during its first two decades of involvement with computers from 1945 to 1965. To provide additional perspective, I will draw comparisons between the IBM case and several efforts to imitate its success. These include the failed attempts of GE and RCA to enter the computer business, the mixed record of the British in fostering an institution comparable to IBM, and the spectacular success of the Japanese in mimicking the American colossus. My treatment of these imitators will not be exhaustive. I wish simply to draw attention to common elements that help explain success and failure in the computer industry and to examine whether those elements fit the theory of Nelson and Winter.

The point of this exercise is to provide an empirical test of a theory that holds great promise for those of us who believe bureaucratic organizations and technical innovation must be brought to the center of discussions of economic change. Of the many attempts to construct such a theory, I find that of Nelson and Winter by far the most attractive. Thus far, however, Nelson and Winter have addressed their work primarily to economists, for whom they have a rather devastating message. Expecting resistance, they quite sensibly have steered clear of anecdotal evidence and have sought to keep the discussion as much as possible on the theoretical grounds economists prefer. Models, not examples, predominate. I would find the theory more persuasive, and

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perhaps more useful, if it were supported by some empirical studies. Since any theory that purports to explain modern economic growth must be able to explain plausibly the course of development in the computer industry, it is a logical candidate for study.

The central argument of this paper is that, on the whole, the theory of Nelson and Winter holds up remarkably well to this test, and that the computer industry provides an outstanding example of the process of economic change they describe. During its formative stages in each of the three countries studied, the industry followed a course that can be explained in terms of the organizational capabilities of existing business institutions and the market pressures that acted as a selection mechanism upon them. IBM succeeded because the hothouse of the Cold War computer industry rewarded it for what it already was; GE and RCA stumbled because their established strengths mattered less in that environment. The British industry languished under the twin burdens of a sluggish market and a deceptively weak leading firm; the Japanese flourished when state-stimulated markets drew out capabilities of firms whose histories resembled those of IBM.

The bulk of this paper seeks to provide a basis for these generalizations, but in the process it also points up certain aspects of the theory that might require further elaboration and perhaps even some revision. At the end, I will discuss some of these and ponder their implications for the role of theory in business history.

A Brief Synopsis of the Theory

Before turning to the computer industry, let me summarize briefly the salient features of the theory. I draw here primarily on ideas presented by Nelson and Winter in their 1982 book *An Evolutionary Theory of Economic Change*. There Nelson and Winter replace the classicist's image of a sea of free producers with a portrait of the economy as consisting of a fairly limited number of established firms or organizations. Firms, like organisms, possess various attributes and abilities. Nelson and Winter refer to these as "organizational capabilities," which ordinarily are expressed in a set of "decision rules." These capabilities involve a great deal of routine, but they also undergo constant modification, in part as a result of deliberate efforts to solve problems and in part because of random events (exogenous shifts in demand caused by events such as a war or a radical technical breakthrough). The market constantly winnows out those modifications or adaptations that do not result in profits.

At its core, this theory rests upon an analogy between firms and skilled individuals. It asks us to think of firms as possessing certain deeply ingrained habits or routines, much like skilled practitioners. Such routines exhibit three key features. First, they are "programmatic," meaning that they generally involve a sequence of actions. In a firm, the sequence might link together many people or subunits. Second, they are undergirded by "tacit knowledge"--knowledge that one has but does not think much about and often cannot articulate fully. Third, they involve many choices, but usually these are made automatically, without awareness that a choice is being made [Nelson and Winter, 1982, p. 7]. Just as craftsmen develop their skills through practice, firms acquire these routines by doing. Over time, they come to possess a body of routine behaviors that is so deeply embedded in the firm that it is taken for granted. No one may even be able to articulate it or explain how it is passed on and maintained.

A firm *is* its routines, for better or worse. Market conditions may reward a firm for its routines or penalize it. But we should not expect a firm to break dramatically from its routines, any more than a skilled craftsman can suddenly change course in midcareer. Indeed, change for an organization might be even more difficult than for an individual because the comparative weakness of central control makes conscious, deliberative choice difficult. Nelson and Winter are emphatic on this point:

> One cannot infer from the fact that an organization functions smoothly that it is a rational and "intelligent" organism that will cope successfully with novel challenges. If anything, one should expect environmental change to make manifest the sacrifice of flexibility that is the price paid for highly effective capabilities of limited scope [Nelson and Winter, 1982, p. 126].

Even when a firm does change in response to the environment, those changes will strongly resemble what came before. Chiding those who operate under the assumption that a firm can pursue any response and become anything it wants to be, Nelson and Winter conclude that

> it is quite inappropriate to conceive of firm behavior in terms of deliberate choice from a broad menu of alternatives that some external observer considers to be 'available' opportunities for the organization. The menu is not broad, but narrow and idiosyncratic; it is built from the firm's routines, and most of the 'choosing' is also accomplished automatically by those routines. This does not mean that individual firms cannot be brilliant successes for a short or long period: success or failure depend on the state of the environment . . . . Efforts to understand the functioning of industries and larger systems should come to grips with the fact that highly flexible adaptation to change is not likely to characterize the behavior of individual firms. Evolutionary theory does this [Nelson and Winter, 1982, pp. 134-35].

These passages capture the essence of the argument as I understand it and will apply it to the computer industry. When I conclude that the industry fits the theory, this is what I have in mind. Even in an industry often characterized as experiencing revolutionary change, we can detect substantial elements of continuity. The shape of the new can be seen in what came before if one looks closely at the embedded capabilities of the firms involved and pays particular attention to what Nelson and Winter refer to as the "programmatic" nature of their routines. Much of the apparent change resulted not so much from conscious choice as from the "automatic" functioning of routines that had a built-in capacity for innovation along certain lines.

The United States

The story of computing in the United States through the mid 1960s can largely be boiled down to one issue: how and why did IBM come to occupy its dominant position?[1] By the mid fifties, IBM had secured approximately 85 percent of the domestic market, a share it

1 This section of the paper is based primarily on my own monograph, which is currently in progress [Usselman, 1993]. Full, detailed references are not yet available.

would retain (if we treat personal computers as a separate entity) for the next three decades. The company enjoyed a similar position in much of Europe and Asia as well [Brock, 1975; Flamm, 1988]. How did this happen? My answer is simple. The war brought forth a "new" technology--the computer--and dramatically increased the demand for it. Much of this demand came initially from the American government for reasons having to do with the Cold War, but private-sector demand proved vigorous as well. Like most "new" technology, the computer had important antecedents, and existing firms had developed capabilities related to those antecedents. None had done so more thoroughly than IBM. Despite some superficial differences between computers and the earlier tabulating equipment that had formed the core of IBM's business, computers involved a mix of knowledge and capabilities that matched those existing at IBM extraordinarily well.

To appreciate this match, we need to understand some things about the nature of computers and the nature of IBM's business prior to the war. Let's begin with computers.

What we think of as the modern, programmable computer had its proximate roots in the 1930s and World War II. A number of scientists, mathematicians, and engineers, working as individuals or in small groups, built one-of-a-kind machines that could, with some adjustment, perform various complex calculations. These efforts took place in many countries, almost always in university laboratories. With the onset of war, most of the calculations arose in the course of military projects, such as the compilation of ballistics firing tables, the processing of information obtained from radar, and the breaking of codes. In the United States, the ballistics problem gave rise to the most conspicuous efforts, most notably the ENIAC machine developed by Eckert and Mauchly at the University of Pennsylvania and the Mark I designed by Howard Aiken at Harvard. For reasons of security, the work associated with code-breaking and radar remained out of public view, but key figures within the emerging military/university/industry research complex were well aware of it. The American radar effort, located in the giant Radiation Laboratory that occupied much of the MIT campus during the war, had drawn together engineers and scientists from throughout industry, academia, and the military. After the war the participants scattered, bringing knowledge of electronics to many corners [Flamm, 1988; Katz and Phillips, 1982].

Apart from their staggering speed, perhaps the single most important feature of the new computers was that they had no single, specific use. They could be programmed to perform different tasks. Indeed, their expense made it essential that they be programmed to perform different tasks. Admittedly, those tasks initially did not seem all that diverse. Most involved complex calculations based on differential equations. Code-breaking represented a different application with important implications, but it was done in secret by the same sorts of people--mathematicians--using similar thought processes. It took a truly brilliant and prescient individual, such as Alan Turing, to recognize that those methods of reasoning could be used to resolve all sorts of problems [Hodges, 1983]. Even when applied to calculations, however, the computer had to be tailored or programmed to receive certain information, manipulate it in particular ways, and print out or store the results in a specific format. The tailoring process involved many things--the logical arrangement of circuits and switches, instructions encoded in language read by the machine's memory, input devices, storage, and printers (the latter three known collectively as peripherals). Over time, as innovations in magnetics reduced the cost of memory and users continually discovered new applications for computers, more and more of this programming came to involve language [Pugh, 1984]. Early on, switches and circuitry were very important, and they remained an influential factor even with the rise of languages. Peripherals, though often neglected by historians, figured prominently throughout.

The task of arranging circuits logically, programming machines, and combining peripherals in various configurations to perform different tasks would itself have sustained a dynamic technological frontier in the postwar era. Before scientists and engineers went far down that path, however, a second frontier opened. This was solid-state technology. The most famous example, the transistor, was announced in 1947 by Bell Labs. But the transistor was really just the tip of a gigantic iceberg. Drawing on an extraordinary base of knowledge about the electrical, magnetic, and photochemical properties of materials, electronic componentry underwent continual innovation that together produced a "revolution in miniature," culminating in the integrated circuit of the early 1960s (an innovation whose performance would subsequently be improved by orders of magnitude through a sustained effort at manufacturing engineering) [Braun, 1978; Flamm, 1988; Lewin, 1982; Mowery, 1983]. This ongoing revolution had obvious implications for computing. Now the balancing act inherent to computer installations would not only involve a mix of circuitry, programming, and peripherals; it would also have to incorporate continually changing componentry.

In terms of the evolutionary model, the period from the late thirties through the late forties had produced a series of random events. Two technical mutations had appeared--the electronic computer and the beginnings of solid state--and military considerations had prompted the American government to provide a vibrant market for both. With the exception of AT&T, these random events had occurred almost independently of established business organizations. Because of its unique relationship with the United States government, moreover, AT&T would not itself attempt to exploit the mutations commercially, but it would facilitate their diffusion to others through licensing agreements and a program of technical symposia.

Now, what of IBM, the firm that would prove the most important of the "others"? At the onset of war, IBM was a solid, moderate-sized corporation that leased electromechanical accounting equipment manufactured at its plant in Endicott, New York. Led by Thomas Watson, a graduate of John Patterson's NCR school of management, the company had a reputation as an outstanding sales organization. IBM salesmen worked continually to build their "installed base" of leased machines, which each month earned them and IBM rental income. Salesmen could, of course, increase their base by attracting new customers, but they could also do so by persuading existing customers to use novel arrangements of IBM equipment to perform new tasks. The production facility in Endicott operated as a mechanical job shop, responding to requests from the field for solutions to particular problems. It constantly took gears, ratchets, and relays obtained from outside suppliers from which it produced novel machines, and it devised numerous ways of joining counters, printers, and other machines in complex installations. Naturally, the mechanics at Endicott routinely looked for opportunities to reduce the variations and build in volume. Sales statistics and education programs helped the company strike a balance between novelty, which generated revenue, and standardization, which produced economy. The production facility also worked in close collaboration with engineers who installed and maintained the equipment in the field [Cortada, 1993; Sobel, 1981; Usselman, 1993].

In sum, IBM was an organization whose business had naturally fostered these qualities: salesmanship that required close attention both to technology and to the particular requirements of each customer, regular exchange of information between the field and the plant, flexibility in production, and a willingness to compromise. In my view, these qualities put IBM in an excellent position to adapt to the electronic computer and the solid-state revolution. Some observers, reflecting on this situation, have argued that IBM behaved in a highly unusual (and remarkably enlightened) fashion in making this transition because the electronic computer ultimately made the company's installed base of electromechanical accounting equipment obsolete. I believe this argument represents a profound misreading of the situation--one that fails to comprehend the nature of technical knowledge in the data processing business, overlooks the importance of existing organizational capabilities, and neglects market conditions. A brief synopsis of IBM's history from 1949 to 1965 will bear this out.

IBM made the transition from electromechanical accounting equipment to electronic computers by pursuing two paths. One was to go after the emerging market for large, scientific machines, which was funded largely through defense contracts. The other was to begin to convert some of its established electromechanical equipment to electronics and to build some degree of electronic programmability into it. Through much of the 1950s, these efforts remained conspicuously separate. The former was centered in Poughkeepsie in a new facility built during the war; the latter remained anchored in the original plant at Endicott. But despite this separation, which many at Poughkeepsie actively tried to foster at the time and which many observers have subsequently exaggerated, the two facilities shared important traits. Each took basic components and arranged them in complex machines that were leased to customers and maintained by IBM in the field. Working in collaboration with their customers and their assemblers, the field force tailored the machines to perform a variety of specialized tasks. Computers, in other words, called forth many of the same qualities as the older technology.

The more significant differences between the activities at Poughkeepsie and Endicott during the early fifties had to do with the market. Most of Poughkeepsie's customers were sophisticated scientific and engineering organizations who leased their machines with defense funds. (The first major product initiative, later named the 701, was originally called the Defense Calculator.) These consumers differed considerably from those in IBM's traditional business accounting market, and one might reasonably ask why IBM pursued them. Several factors help explain this move. First, many of the early scientific computers had been built from modified IBM punched-card equipment. Second, the company had a long tradition of doing business with government, and its chief executive officer was a close friend of the Roosevelts. During the war it had sponsored the Mark I project. Third, IBM was a market-oriented company, and scientific computing represented an obvious opportunity, one that did not threaten its established base at all [Bashe, 1986; Usselman, 1993].

That market was especially attractive because of the approach the government took to computing. From the beginning, government did not attempt to target firms with the most impressive research organizations. In other words, it did not pursue a "supply-side" approach, in which it assumed that money spent on research would ultimately yield computers. Instead, the vast majority of its support came in the form of purchase orders for computing power. The government, acting as an "informed first user," set goals and put out bids to have them met. Moreover, it did so not through a single, coordinated plan, but by placing money in the hands of many different organizations that each put out their own contracts for bid. Each of the armed services acted as a consumer, as did the laboratories of the Atomic Energy Commission, as did the large manufacturers of aircraft operating under government contract. In effect, the government set up a market for powerful computers--a market of informed users who expected to exert sufficient input into the design of their machine to insure that it performed the particular operations they desired [Bashe, 1986; Broack, 1975; Flamm, 1988; Katz and Phillips, 1982; Lewin, 1982; Nelson, 1982a; Mowery, 1983].

This was a market that suited IBM perfectly. The company's entire culture was dedicated to the task of meeting specific data-processing problems in the field. The only significant difference between large electromechanical data-processing installations and these machines was that the computers would use vacuum tubes instead of electromechanical relays and would involve a staggering amount of wiring. But these differences appear trivial when placed in the total context of the task. Computers called for extensive sales, maintenance, programming, and field engineering. Within the plant, the company would look as always for ways to build standardization into the machines while retaining sufficient flexibility to meet the demands of each user. At this point, before the advent of lower-cost memory enabled users to reprogram the machines easily, such custom tailoring often involved the wiring itself, just as customizing the older equipment involved unique arrangements of gears and ratchets. One of the greatest challenges in such work, IBM had long since learned, was to keep track of design changes as the machine moved into production and out into the field. This task required massive record keeping and close cooperation among engineers responsible for design, assembly, and service. In tackling those jobs, IBM drew freely on personnel who had performed similar tasks at Endicott.

Purchasers recognized these qualities in IBM and favored the company because of them. This was certainly true in the case of the SAGE contract, a massive anti-aircraft project funded by the Air Force that called for 23 pairs of computers operating in real time. The Air Force relied on Jay Forrester of MIT to design these novel machines, but when it came time to build them it chose IBM over several other firms favored by the academic designer. The Air Force cited IBM's experience with assembly and service as the critical factors influencing its choice.

The SAGE contract proved extraordinarily important to IBM, because it introduced the company to a variety of military-sponsored technical efforts aimed at reducing the costs of assembling or packaging electronic circuits [Lewin, 1982; Pugh, 1984; Usselman, 1993]. Especially prior to the advent of the integrated circuit, packaging was perhaps the most important element of computer production. It was where logical design, componentry, and custom-tailoring intersected. SAGE and subsequent government contracts for state-of-the-art machines, such as STRETCH, helped IBM build on its established expertise as an assembler and stay abreast of the latest developments in solid state techniques [Bashe, 1986].

Throughout this critical early period of government support, IBM benefited from a quality that might at first seem a detriment in an environment of rapidly changing technology. That quality was humility. In short order, computing had opened two technological frontiers--logical design and solid-state componentry. It was very easy for people working at those frontiers to feel a certain hubris. Many of the practitioners were physicists and mathematicians. The work they did was new and scientific, and yielded fame and Nobel prizes. IBM filled a far less glamorous middle ground. It purchased components, as it always had, and it let its customers have input into the logical designs. This attitude permitted IBM to move to the center of knowledge in the industry.

Humility also aided IBM during this period by helping prevent it from ignoring potential customers. Many organizations working on computers focused almost exclusively on the high end. Perhaps the most apt comparison is Engineering Research Associates (ERA), a company that concentrated on building computers for the most sophisticated users. "Because of the nature of its market," Kenneth Flamm has noted in his excellent history of the computer industry,

> engineering considerations dominated ERA's business orientation . . . . In sharp contrast with firms seeking a commercial market, ERA experienced little feedback from users and little direct contact with what remained a relatively unknown market. The emphasis on technical sophistication over marketing, it may be argued, persisted in the computer companies that the engineers brought up in ERA went on to found [Flamm, 1988, p. 46].

As IBM entered the scientific market, it never lost sight of the commercial market and the potential connections between the two. Most significantly, the company did not isolate work on the large computers in a separate scientific or defense wing. As it worked on the 701, IBM simultaneously developed the 702 for business purposes. The two programs shared many of the same personnel and the same technology. Here again, one can see that an established characteristic of the firm--its tradition of entering many markets and seeking to transfer lessons learned in one market to the others--ultimately contributed to success in the computing business.

In actuality, however, IBM's efforts to transfer the fruits of its work on scientific machines directly to the commercial market seldom worked as well as planned. The real growth in business computing came instead from the second path, the operations at Endicott, where engineers developed programmable electronic calculators. Their first big success was the 650, which ultimately sold in the thousands; later they generated the 1400 series, a spectacular success of the early sixties that made computing far more common in business than it had ever been before. The Endicott facility also produced a series of input-output devices that helped develop the market for both large and small computers. Though these products made use of electronics, they also drew extensively on the mechanical skills available at Endicott. Printers and disk storage devices in particular were as distinguished as much for their rapid, precise mechanical motions as for their logical design [Bashe, 1986; Usselman, 1993].

The introduction of these products perhaps lends some support to the contention that IBM showed extraordinary daring in making its established line obsolete. But again, I would urge that the developments at Endicott be seen in the context of IBM's previous history and the emergent market for data processing. By the time of its move into electronics, IBM had a long history of making its own machines obsolete. Its sales force had long since learned that continual change, if it produced some new capabilities, was the surest path to larger contracts. Greater calculating power would almost certainly lead customers to spend more on novel methods of printing or to do additional tasks. Someone might have drawn a sharp division between electromechanical devices and electronic ones, but to do so would have been out of the ordinary, at least at IBM. In assessing this situation, moreover, we should remember that the market for data processing was growing rapidly. Machines taken out of service at one installation could readily be placed in another. Many were shipped overseas, where depression and war had created an enormous pent-up demand that domestic manufacturers could not meet. No firm was better positioned to perceive these marketing opportunities than IBM, the largest accounting machine company, and one with established outlets around the world [Sobel, 1981; Usselman, 1993].

By the mid fifties, IBM had achieved a commanding position in computing. Drawing on its established capabilities, it had responded to all segments of a vibrant market. Flamm has noted that by 1950 one could clearly identify four separate approaches to computing: 1) large commercial machines such as Eckert and Mauchly's Univac, the successor to ENIAC; 2) large scientific machines such as that designed by the mathematician John von Neumann for Princeton's Institute for Advanced Studies; 3) computers for use in real-time control applications, such as that under development at MIT in Project Whirlwind; and 4) small machines that might appeal to cost-conscious consumers [Flamm, 1988, p. 105]. I would add that IBM had at that time already become involved in all four, and that by 1955 it had assumed the lead in all four, with its 702/705, 701/704, SAGE, and the 650, respectively. Each of these machines, moreover, had given birth to sustained efforts to generate further development.

Because IBM ended up with development efforts aimed at all segments of the market, it was then in a position to see and feel pressures from what would soon emerge as the central recurrent dynamic force in the computer industry: the convergence of machines designed for one market with those designed for another as the availability of new memory increased programming capacity and as changes in componentry improved processing power. From the mid fifties on, this issue continually created problems within IBM as its machines competed with one another in the marketplace and its development efforts overlapped. The problems within development were compounded by the continually advancing technology of solid state, which constantly blurred divisions between component manufacture and logical design. Mervin Kelly, the former research director of Bell Labs whom Tom Watson, Jr., had hired as a consultant, warned Watson that IBM would lose the capacity to design computers if it failed to integrate backward into the components business. Kelly predicted that established component producers that also had experience designing, building, and marketing electronic products, such as RCA and GE, would eventually dominate the industry. Though few did so as early as Kelly, in time many observers in the business press expressed similar judgments. Managers at GE and RCA laid plans for the move [Usselman, 1993].

During the late fifties IBM addressed these pressing matters. It struggled to sort out its development efforts and to master solid-state manufacturing. Steps taken during this period would eventually culminate in System/360, a single line of computers that would replace all other IBM machines, run the same programs, and contain solid-state circuits of the same standard design manufactured from scratch entirely within IBM. No other product announcement would have a more profound effect on the computer industry at least until the coming of the personal computer [Pugh, 1991; Usselman, 1993].

Space does not permit a full accounting of the tortuous course that culminated in the production of System/360, but one feature of the process deserves emphasis. Even as IBM integrated backward into component production, its traditions of assembly, packaging, flexible production, and feedback from the sales force and field engineers remained essential factors in its success. The key remained not simply to master components but to strike balances among componentry, logical design, and markets. Within componentry, moreover, one needed to strike balances between performance and manufacturability. Once again, IBM's tradition of product engineering and its lack of technical hubris proved extraordinarily useful.

Drawing on its established capabilities in circuit assembly and packaging, IBM moved in two steps. First it developed a new solid-state package using transistors obtained under license from Texas Instruments. (IBM's established position in the marketplace no doubt made it an attractive plum for Texas Instruments.) The new package, known as Standard Modular System or SMS, introduced IBM to the world of chemical or "wet process" manufacturing. This technology formed the basis of its 1400 series computers and other large-scale machines. The line operated at Endicott, where its designers again took advantage of the available mechanical skills to build the necessary conveyers and other materials-handling equipment.

Then, for its System/360 series announced in 1964, IBM took the expertise acquired from TI and developed its own internal component production facility. Though constructed near the Poughkeepsie plant, a management team from the SMS production area ultimately took charge of running this operation, with ample assistance from personnel borrowed from TI. Significantly, IBM in building this facility struck a fundamental compromise, choosing not to develop the new integrated circuits and instead concentrating on building a production line of great flexibility that could readily respond to shifts in demand and keep track of design changes. True to its heritage, even as it moved into extraordinarily capital-intensive process manufacturing, IBM did not want to sacrifice the flexibility it had come to rely on as an assembler of customized machines. (It gained additional flexibility by continuing to rely on the SMS format for many of the peripherals.) Though System/360 is often lauded as bringing a high degree of order to the market by consolidating IBM's offerings in a few standard models, in reality the system included machines of countless variations.

Contrary to predictions, RCA and GE never competed successfully with System/360, despite conspicuous efforts to market similar lines. Though my conclusions are speculative, since I know of no detailed studies of computer production at either firm, I would suggest that the poor match between these firms' organizational capabilities and the tasks inherent to computer production hold the key. Neither RCA nor GE had much experience marketing complex products to business people who were not scientists and engineers [Graham, 1986]. Since feedback from the business machines market remained an important ingredient in IBM's success, the absence of an established marketing and support team almost certainly handicapped its two competitors. As Kelly's remarks to Watson suggest, RCA and GE no doubt hoped that their traditions of manufacturing their own components would compensate for deficiencies in marketing. But IBM's experience with backward integration into component production suggests to me that those firms' experience with vacuum tube production might well have worked to their detriment. Manufacturers of vacuum tubes did not generally achieve success with semiconductors, an industry that came to be dominated by new firms [Dosi, 1982; Lewin, 1982; Mowery, 1983]. Companies that manufactured components, moreover, often tended to exaggerate their importance and neglect packaging. Again, the IBM case suggests that packaging remained essential even with the rise of solid state. Though the materials changed, the outlook and approach remained much the same. And the most critical new technical processes, such as photoetching, would have been as unfamiliar to RCA and GE as they were to IBM. In sum, like many other observers of the industry, Kelly exaggerated the importance of one technical feature and underestimated the importance of organizational capabilities that facilitated coordinated action on many features at once.

Britain

In 1965, at virtually the same moment IBM delivered its first System/360 computers, the economist Christopher Freeman published a report on the international electronics capital goods sector in Britain's *National Institute Economic Review* [Freeman, 1965]. In his extensive discussion of computing, Freeman in effect addressed the same question I have just considered--why had IBM succeeded?--but with an added concern for how the British might best respond. To a remarkable degree, Freeman's analysis lends support to the thesis that the combination of a robust market and existing organizational capabilities explained IBM's remarkable emergence.

In preparing his report, Freeman interviewed managers of many of IBM's competitors around the world. "Almost all firms interviewed," he reported, "attributed the United States' success to two principal factors: a technical lead in many products, and the vast American military and space budgets" [Freeman, 1965, p. 51]. As I and others have emphasized, the key to American government support appeared to rest more in its procurement policy than in its direct support for R&D. "Some [European] firms believe," reported Freeman, "that the much larger American home market and the stimulus to demand from the government programs are more important in explaining the American lead than the government support for R&D as such" [Freeman, 1965, p. 72]. Freeman concurred with this opinion. "Almost all the early demand in the United States was from the military market. Few people then envisaged the large-scale use of computers for data processing, and both government and industry thought mainly in terms of military and scientific applications" [Freeman, 1965, p. 59].

While freely embracing the view that military demand had played a major role, Freeman spent the bulk of his article explaining why military demand alone did not account for IBM's success. The "military-space market is very different from the normal commercial market," Freeman cautioned.

> The products are more specialized and expensive, being made to more exacting specifications. Both in America and Britain some firms which have concen-

> trated on the military market and have the largest military R&D contracts have a less satisfactory record in the civil market and as exporters. Thus the supposed benefits of American government programs are not so straightforward as appears at first sight" [Freeman, 1965, pp. 51-52].

These cautionary remarks led naturally to a discussion of IBM, which clearly could feel plenty of satisfaction with its record in the civil market and as an exporter. Freeman described IBM as "a very successful and fast-growing office equipment company with a strong tradition of product innovation before it began to manufacture Electronic Data Processing (EDP) equipment. It already had a strong world-wide sales organization and field force of engineers" [Freeman, 1965, p. 59]. Freeman also drew attention to IBM's personnel policies and to its customer relations, which he saw as all of a piece. "Few companies can have given so much attention to the selection and training of their own employees," he observed, "and to the training of their customers" [Freeman, 1965, p. 59].

The significance of these attributes became clear when Freeman assessed the nature of the computer business. Significantly, Freeman downplayed the importance of the inventor and emphasized the firm. "American firms' technical and commercial lead since the Second World War has depended not so much on their capacity for original invention or completely new products as on their success in developing a series of greatly improved models embodying new features in design and far higher standards of performance," he wrote. "The nature of the industry is such that it is not necessary to invent everything in order to secure a strong technical or commercial lead . . . . What is necessary is to have a strong development and engineering capacity, so that inventions made elsewhere may be rapidly assimilated, imitated, utilized, and improved upon" [Freeman, 1965, p. 63]. "The transition from laboratory prototype to successful commercial production and sales calls for rather different resources and skills [than those of the inventor]," Freeman noted in another passage. "This transition is difficult and expensive for such complex products as electronic capital goods. The firms which succeeded combined a well-organized research, development, and test programme with good production planning and technical service" [Freeman, 1965, p. 62].

Again and again, Freeman stressed the importance of information flows in the computer industry. "The development process in the electronic capital goods industry consists largely of devising methods of assembling components in new ways, or incorporating new components to make a new design, or developing new components to meet design requirements," he explained. "Consequently, there must be close collaboration between end-product makers and component makers." Significantly, Freeman noted that "this does not necessarily mean that there must be vertical integration," since "specialist component makers may offer some economic advantages." "In part," he wrote, "this may be done by licensing and know-how agreements with other firms in the industry, or with governments, in part by recruitment or outside consultancy" [Freeman, 1965, p. 63]. "Successful development," he concluded, "depends on a good deal of give and take between firms" [Freeman, 1965, p. 65].

Writing at the time of IBM's integration backward into components, Freeman devoted more attention to cooperation and information flows in the design and production stages than in the area of customer relations. But he clearly appreciated the importance of field engineering and sales as well. Freeman viewed customer relations as especially important in the business market, and in discussing them he reiterated his belief that success in the military or scientific market did not necessarily lead to commercial success. "The distinction between the 'scientific' and the commercial 'EDP' markets is important," he noted. "Sometimes they may use the same machines, although with different configurations and peripherals. But, whereas the 'scientific' customer usually knows a good deal about the machine and can do a lot of his own 'software' and maintenance, the 'commercial' customer usually needs a great deal of training, advice, and assistance from the manufacturer. The field force in the EDP market must be much larger, and firms which are successful in one market will not necessarily be successful in the other" [Freeman, 1965, p. 61].

I have dwelled at some length on Freeman's analysis because I believe it represents a contemporary account that lends considerable support to my thesis, without itself being directly influenced by the theory of organizational capabilities. Interestingly, however, Freeman had much more to say about American developments than he did about the performance of British computer firms. In effect, he argued by implication, accounting for British failure not so much by considering the subject directly but by analyzing the success of its rivals. Presumably British firms and the British government did not do what IBM and the American government did.

Two recent historical studies of British institutions lend considerable support to that presumption. The first is Martin Campbell-Kelly's fine institutional history of ICL, the "British IBM" [Campbell-Kelly, 1989]. Because ICL has absorbed so many of the data-processing firms in Britain, including BTM (British Tabulating Machines) and Powers-Samas, the two British manufacturers of electromechanical accounting equipment before World War II, Campbell-Kelly's book provides an overview of the data-processing industry in Britain during the twentieth century. The second study is John Hendry's *Innovating for Failure*, which traces the actions taken by the British government's National Research and Development Corporation (NRDC) to foster the computer industry [Hendry, 1990]. These two books converge on the critical period from 1949 to 1959, when the British computing industry fell dramatically behind the American despite a comparatively similar starting position. In other words, they focus on British institutions during the period for which Freeman has so perceptively analyzed American performance. The books also converge on a common theme: failure.

Space does not permit a full discussion of these accounts. Here I wish only to sketch the authors' answers to two questions: why was BTM unable to grow at anything like the pace of its American counterpart, IBM, and why did NRDC have so little success in fostering the computer industry?

Campbell-Kelly's history suggests to me that much of the explanation for BTM's sluggish performance and its inability to follow IBM with vigor into electronics and computers rests in the company's prewar roots. BTM had operated under license from IBM. It had manufactured machines like those built in the States by IBM and leased them in the British market. On the surface, it possessed the same organizational capabilities as IBM, and for that reason many in Britain always expected it to follow a similar course in computing. In reality, however, BTM had never developed the vitality that characterized IBM before the war. In particular, it lacked the vibrant production engineering mechanism that proved so instrumental to

IBM's success with computing.

Another problem BTM faced was that it stood outside the university research establishment. This was true initially of IBM in the United States as well, but after the war that changed under the influence of the liberally funded, procurement-driven American military. In the United States, moreover, universities and government had never established very firm connections, so IBM and other corporations faced little resistance from entrenched interests. In Britain, however, universities and government had established close links by the time of the war, with business drawn into the alliance only through the mediating agency of the consulting engineer. After the war, Britain's much smaller defense budget did not have the strength to dissolve those traditional bonds. University research remained closely tied to government and the military. This skewed efforts away from development and manufacturing [Mowery and Rosenberg, 1989]. In the specific case of computing, this had the effect of keeping Britain's remarkable code-breaking machines and the pioneering computers developed at Manchester University separate from BTM and other manufacturers. In 1949, moreover, BTM severed its ties to IBM, thus depriving itself of ready access to an alternative source of computer designs.

The British government created NRDC in large part to redress this situation. This publicly owned corporation was supposed to insure that patents generated through publicly supported research were made available to private corporations for rapid commercial exploitation. NRDC would offer financial support for firms willing to use the patents. Lord Halsbury, the director of NRDC during its first decade, identified the computer industry as an obvious candidate for support. Halsbury, who made frequent trips to the United States and closely monitored IBM's early successes in marketing electronic calculators and computers to its traditional business customers, became convinced that the British computer industry would succeed only if one of its electronics firms merged its technical expertise with the marketing experience of either BTM or Powers-Samas. But Halsbury lacked the resources to force the issue. Out of concerns for fairness, the government had restricted the funds available from NRDC and had insisted that they be repaid. Firms accepting these funds, moreover, had to agree to turn all patents generated in the course of the subsidized project back to NRDC. With such scant bait, Halsbury had little chance of luring firms into the organizational alliances he wisely desired.

The combination of its research traditions, NRDC's limitations, and BTM's incompetence left Britain without an organization with the capabilities of IBM. Behind these organizational matters, I believe, lurked another more basic difference with the American situation. The British market for data processing lagged behind the American market, even when adjusted on a per capita basis, in large part because the British lacked enthusiasm for data processing. I cannot provide extensive evidence directly supporting this hypothesis or even offer many suggestions about what caused the lack of enthusiasm.[2] The subject of public attitudes toward computing remains largely unexplored. (Here is an important opportunity to explore cultural inputs into the process of technical change.) I would, however, point out that IBM has long perceived the British market as sluggish. During IBM's association with BTM, the British firm never met its parent's sales objectives for it. Though correspondence among IBM and BTM managers cited by Campbell-Kelly suggests that IBM found ample cause for blame within BTM, my guess is that consumer taste accounted for much of the failure to meet quota. It is much easier to exert pressure on one's subsidiary than to alter conditions in its market. The comparative lack of vitality within BTM before the war stemed in large measure, I suspect, from the fact that it did not enjoy nearly the degree of feedback from customers as that which propelled so much change within IBM. The sluggish market deprived BTM of the engine that drove IBM to develop its organizational capabilities, setting in motion a vicious cycle because BTM then lacked the ability to generate products that might have spurred demand.

2 At this point my discussion bears considerable similarity to the wider issue of the role of organization in Britain's relative economic decline, growing out of the work of Chandler and Lazonick [Chandler, 1990 and 1992; Elbaum and Lazonick, 1986; Lazonick, 1991]. Most critics agree that organization figured prominently, but some have argued that cultural factors, including a general resistance to innovation, must also be taken into account [Broadberry and Crafts, 1990 and 1992; Coleman, 1987; Davenport-Hines and Jones, 1987; Kirby, 1992; Walker, 1980; Weiner, 1981]. Curiously, the literature on British decline contains virtually no references to the computer industry [above references, plus Pollard, 1982].

In Hendry's account of NRDC, one can catch glimpses of Lord Halsbury's frustration with British consumers. Returning from his trips to the United States, Halsbury repeatedly tried to convince people in Britain that business could provide a market for computers. When these efforts failed, he even suggested that British computer companies pursue the American market. Halsbury's one significant accomplishment during the decade was in arranging for government to purchase ten computers.

Freeman, too, lends some support to this contention. Freeman believed British computer firms had stayed too closely tied to the scientific/government market. This orientation had skewed their development efforts and retarded growth. His comments about the difficulty of moving between the scientific and commercial markets reflect this concern. Apparently Freeman did not attribute this behavior primarily to decisions made by managers and government officials, but to the environment in which those managers and officials operated. For when Freeman turned from description to proscription, he did not call for direct support of institutions that would follow a different course. Instead, he called for government to fund projects that would create new markets for computers. Freeman suggested that government establish a national network and support the development of computer applications in education. He believed this approach would help nurture institutions with the capabilities he admired.

British public policy did change in response to System/360, but not in the direction Freeman advocated. Instead, the British government directed most of its energies toward encouraging a series of mergers that culminated in the formation of ICL in 1968. The new firm combined BTM, which by then had merged with its old competitor Powers-Samas and taken the name ICT, with most of the electronic computing and components manufacturers in Britain. More than a decade late, it fulfilled Lord Halsbury's goal. ICL was clearly modeled after IBM. It was a fully integrated manufacturer with a desire to pursue all markets. One observer has aptly characterized it as a "national champion," a company anointed by government to provide leadership. Several other European nations pursued a similar strategy in response to System/360 [Flamm, 1988].

The strategy has not worked, for reasons Freeman appreciated at the time and Campbell-Kelly makes clear in his history. IBM had grown organically in soil enriched by government. It had established capabilities before the computer came along, and it had moved gradually to acquire additional ones as the technology changed. Though BTM on its surface appeared to possess the same original capabilities as IBM, it had never developed them as fully. Operating in a much less vibrant market, it had done little to develop the additional abilities necessary to develop and manufacture computers in a timely fashion. Now government had attached to it firms that appeared to possess the necessary skills in componentry, design, and manufacture. Unlike IBM, however, the recently merged British firms were expected to master the critical balancing act among those functions virtually overnight. And government had still taken no measures to sweeten the market. Not surprisingly, then, Campbell-Kelly's book ends with a series of chapters detailing one disappointment after another as each new ICL product fails to meet expectations.

Japan

As is so often the case in the economic history of the past half-century, in studying British failure we find the keys to Japanese success. The Japanese pursued a course remarkably similar to that suggested by Freeman, with some additional public policies that took advantage of the established capabilities of their government organizations. In part by design and in part by accident, the Japanese replicated the conditions that had given rise to IBM. As a result, Japan ended up with an internationally competitive industry led by a company, Fujitsu, that more genuinely possessed the capabilities of IBM than did ICL.

In pursuing this course, Japan may very well have benefited from its comparative backwardness. Prior to World War II, the Japanese had no domestic accounting machine industry. There was no BTM to muddy its waters and confuse the situation. Aside from some experiments at the Nippon Electric Company (NEC), the country had little experience in electronics, either [Flamm, 1988; Fransman, 1990; Sobel, 1986]. The absence of a continuing tradition of relationships between the research establishment and the military may have provided further benefits. Though such relationships had proved quite beneficial in the United States, where the military had received a dramatic increase in funding, the British case had shown that close links between researchers and the military could distort development when defense was funded at a lower level.

Starting with a comparatively clean slate, the Japanese spent the decade after the occupation monitoring developments and gathering information. Lacking an established producer in the data-processing industry, they felt little urgency to respond immediately to the extraordinary changes taking place in the United States and Europe. Japan's established electrical manufacturers concentrated on the more urgent task of rebuilding and expanding its electric power grid and on the less capital-intensive consumer products sector. Meanwhile, two institutions within Japan provided some tentative support for research. The first was Nippon Telegraph and Telephone (NTT), the state-owned telephone monopoly, which operated a research facility known as the Electrical Communications Laboratory (ECL). ECL monitored developments in componentry and circuit design that might have implications for the telephone network. These activities fit comfortably within the lab's traditional role, which was to keep the giant monopoly abreast of developments so that it could make intelligent purchasing decisions. (Unlike AT&T, which built much of its own equipment, NTT traditionally acquired equipment from electrical suppliers such as Fujitsu and NEC, though it often had considerable input into design specifications.) The second institution supporting research was the government's Ministry of International Trade and Industry (MITI), whose Electrotechnical Laboratory (ETL) pursued a program much like that at ECL for the economy as a whole. Together, ETL and ECL accomplished three tasks that would later prove critical. They fostered reservoirs of knowledge about componentry; they put NTT and the Japanese government in a position to be informed, intelligent consumers of electronic machines; and they helped further traditions of cooperation among potential consumers, electrical equipment manufacturers, and those with a knowledge of components [Flamm, 1988; Fransman, 1990; Johnson, 1982].

As the fifties progressed, pressure built within the Japanese business community to acquire data-processing equipment. With no established domestic producer, the government agreed in 1954 to let

IBM sell equipment through a subsidiary known as IBM Japan. For six years IBM Japan sold equipment manufactured outside Japan to Japanese firms, for the first time establishing an installed base of data-processing equipment in Japanese business. Much of this base consisted of refurbished electromechanical equipment, but toward the end of the 1950s IBM introduced some electronic machines into Japan as well. Meanwhile, established Japanese equipment manufacturers moved tentatively into the market with machines that, like those sold by IBM Japan, would have appeared old-fashioned by American standards. As I have emphasized in discussing the American case, however, old machines would help foster many of the basic skills and organizational abilities as well as new electronic computers would have. By 1961, Japanese firms held 18 percent of the market [Fransman, 1990, p. 27].

Beginning in 1960, the Japanese government began a series of measures designed to bolster the domestic market for computers and insure that Japanese firms enjoyed advantages in pursuing that market. One measure, which might at first seem to contradict my general characterization of the new policies, was to permit IBM Japan to manufacture computers within Japan. In exchange for this concession, however, the Japanese government obtained rights to license all IBM technology. Though many students of the computer industry have argued that such licensing arrangements have little economic significance because the rapid pace of technical change makes licensed techniques obsolete before they can be exploited [Flamm, 1988; Mowery and Rosenberg, 1989], I would suggest that this particular licensing arrangement at the very least sent an important signal to Japanese firms to go ahead and compete without fear. At the same time, moreover, the government hiked the duty on imported computers (including those manufactured by IBM Japan) to 25 percent and established rules requiring the Japanese government (including giant NTT) to buy domestic. These rules applied even to universities, which as in other nations had consistently provided a demand for the most sophisticated machines and an important source of user feedback. In addition, MITI established a new leasing company, the Japanese Electronic Computer Company (JECC), which agreed to purchase machines from the manufacturers and place them in industry. Though the Japanese manufacturers had to buy back at book value any machines returned to JECC, the leasing firm almost certainly helped reduce risks. JECC had access to low-interest loans from the government, which it in effect passed on to computer makers and users; by agreeing to depreciate machines rapidly and lowering their book value, it assumed some of the losses from returned machines [Anchordougy, 1989].

This combination of policies clearly helped build Japan's domestic manufacturers. By 1966, their share of the Japanese computing market had risen to 54 percent [Fransman, 1990, p. 27]. Perhaps more importantly, the government had accomplished this not by targeting particular firms and creating a "national champion" but by seeding the market for computers. Interestingly, when MITI had first proposed the creation of JECC, it had hoped to use the company to shape research and development activities directly. NTT and other consumers of computers had objected, however, so that MITI had to settle instead for a mechanism that worked through the market. As ultimately structured, JECC subsidized the market but did not foreclose competition among Fujitsu, NEC, Hitachi, and others [Anchordougy, 1989]. As Martin Fransman has demonstrated convincingly in his recent study, cooperative initiatives such as JECC have often retained more substantial elements of competition than outside observers of the Japanese computer industry imagine [Fransman, 1990]. By stabilizing prices, moreover, JECC skewed that competition toward technology and performance--much as the military had done earlier in the United States.

After 1966, most government policy affecting computers in Japan came in the form of large procurement contracts issued by MITI and NTT. From 1966 through 1972, MITI conducted the Very High Speed Computer Project, and in 1968 NTT launched the Dendenkosha Information Processing System (DIPS) [Fransman, 1990]. In placing these orders, Japan pursued a strategy that David Mowery and Nathan Rosenberg have called that of a "fast second" [Mowery and Rosenberg, 1989]. It did not attempt to leapfrog the competition; it simply tried to match IBM as quickly as possible. MITI aimed to bring Japan's established electronics manufacturers up to speed with IBM, and the DIPS program set a goal of surpassing the performance of IBM's System/360 in telecommunications networks applications. Another MITI program launched in 1971, known as the Mainframe Computer Project or 3.5 Generation, expressly set a goal of matching the performance of IBM's recently announced System/370 line, the successors to its notorious 360s [Fransman, 1990]. System/370 had led RCA and GE to give up the computer business and had prompted the British to redouble their commitment to the national champion approach [Campbell-Kelly, 1989; Flamm, 1988].

Though these government procurement programs encouraged cooperation, they still retained significant elements of competition [Fransman, 1990]. The government set the technical goals and promised a market, but firms remained free to work out the details. As a result, one could observe in the Japanese industry of the 1970s much the same jockeying among firms that had occurred in the American industry during the 1950s as companies with various organizational capabilities struggled to win contracts and gain control of projects. Fujitsu, Hitachi, and NEC all participated in DIPS, but they pursued separate approaches to the problems posed by telecommunications. Fujitsu, a vertically integrated manufacturing and design organization, sometimes obtained components from Hitachi, but in 1970 it broke off that relationship in favor of one with the American firm headed by Gene Amdahl. Later Fujitsu and Hitachi cooperated in the 3.5 Generation program. Unlike the British and some other European nations, the Japanese government had not anointed a national champion in hopes it would possess the abilities to compete with IBM. It had set a goal of competing with IBM and created a competition that produced organizations with those abilities.

Conclusions and Cautions

In conclusion, let me briefly summarize the course of development in the computer industry as I understand it, then assess how well it conforms to the evolutionary theory of Nelson and Winter.

My story takes as its starting point the simultaneous invention of the electronic programmable computer on the eve of and during World War II. Like most inventions, it had a long way to go before it would become the innovation most of us think of when we hear the word computer. Because of its very nature, the computer would ultimately be defined through a process of compromise. Feedback from users was especially important. The complexity of this process was compounded by a second revolution (or mutation) in componentry, which itself involved compromise between considerations such as manufacturability and performance. More than the computer itself, the solid-state revolution occurred outside of established traditions. The gap between an integrated circuit and a vacuum tube was greater than that between a programmable electronic computer and an electromechanical accounting machine.

What factors most influenced the process of compromise and shaped the course of events that defined the computer? Two stand out: first, the nature of the domestic market and second, existing organizations with established capabilities that made them likely to respond to the market and facilitate compromise. At the end of the war, the United States had by far the most vibrant market, in large part because of military demand but also because of enthusiasm for data processing in the business sector. In that hothouse environment, IBM flourished because its established traditions--especially those in marketing and product engineering--meshed extraordinarily well with the nature of the two new technologies. The British, though holding a similar position at the time of invention, lacked both the market and the organizational capabilities. Britain's policies and organizational traditions, moreover, tended to impede the development of both a vibrant market for computers and the organization best suited to reach such a market. The Japanese, though starting from a position behind both the Americans and the British, ultimately recreated the conditions that existed in the United States after the war. Their government fostered a domestic market and let firms respond to it. Because Japan lacked an established producer of electromechanical accounting equipment, the subsequent struggle unfolded somewhat differently than the American case, but again those firms with established organizational capabilities that best matched the tasks posed by computing technology emerged as the dominant players.

How well does this story mesh with the theory of Nelson and Winter? In its emphasis on established organizational capabilities, especially those that incorporate some degree of change into the routine operations of the firm, my history of computing resonates with the theory. Superior performance occurred where firms that possessed such capabilities encountered a market context that provided a vibrant selection mechanism. My findings also lend considerable support to the efforts of scholars like William Lazonick and Alfred Chandler, who recently have attempted to build a theory of organizational capabilities into historical explanations of comparative economic performance among nations [Chandler, 1990 and 1992; Elbaum and Lazonick, 1986; Lazonick, 1991].

While in these fundamental respects my history of computing supports the evolutionary theory, it also highlights some features of that theory that perhaps require further illumination. In their discussion of routines, for instance, Nelson and Winter acknowledge that their thinking is informed primarily by situations in which a few firms manufacture a single product. Their discussion of innovation and learning-by-doing is heavily influenced by the literature on manufacturing, especially the perceptive studies of Nathan Rosenberg. Similarly, though Nelson and Winter note that their theory can consider organizational innovation as well as technological change and in several passages point out the difficulty of separating the two, they pay attention almost exclusively to technological innovation.

The history of computing strains against each of these simplifying assumptions. Though IBM's established capabilities in manufacturing were important to its success in computing, the real value of those capabilities came from their fluid connections with other parts of the organization. The flow of information between manufacturing and marketing was critically important. This was especially true because IBM and other computer makers were *not* producing a single, uniform product. Product differentiation remained a key to strategy and performance even with System/360, an initiative ostensibly intended to bring uniformity to the market.

The prominence of marketing and its linkages to other parts of the organization relate to a feature of Nelson and Winter's theory that thus far I have not addressed. As they well recognize and acknowledge, the biological process of natural selection cannot strictly be applied to economic affairs because economic species (firms) can actively seek to influence the environment that selects upon them (the market), whereas biological species are selected passively and unknowingly.[3]

3 For purposes of simplification, I will ignore here the growing body of thinking among evolutionary biologists that suggests species might also possess such abilities.

Firms, moreover, can pass on new behaviors they acquire in response to selection pressures, while biological species must rely on unconscious processes of mutation and reproduction to generate change.

Nelson and Winter downplay these inherent limitations in the evolutionary analogy by stressing that much of the response of firms to selective pressures is in fact unconscious, too, but they acknowledge that two types of behaviors pose special challenges to their interpretation. The first is marketing, especially advertising that is intended to support strategies of product differentiation. The other is reseach and development. Nelson and Winter have little to say about the former, though they identify marketing strategy as an important area for further study, but they do devote quite a bit of attention to R&D. Here again, their primary objective is to demonstrate that even research is usually constrained in identifiable ways by established routines. Firms develop certain ways of searching for solutions, and those habits tend to bias searches in certain directions.

Does the case of computing, in which research and marketing seem so prominent, strain the inherent limits of the theory to the point of breaking? I think not. The experience of computing firms lends considerable support to the argument that much of the most critical research and development occurs in the ordinary course of routine operations. Indeed, my conception of the industry indicates that research and development might be even more deeply ingrained in a firm's routines than Nelson and Winter suggest. At IBM and elsewhere, the research that mattered most was linked inextricably to manufacturing and marketing. The marketing force did much of the "searching" that Nelson and Winter see as central to R&D. Just as I would caution against placing too much emphasis on learning and innovation in manufacturing at the expense of that which takes place in other areas of the organization, so I would caution against isolating research and development from the rest of the firm. Searching, like learning-by-doing, seems to have taken place continually throughout the firm.

My other words of warning pertain not to the internal characteristics of firms but to the environment in which they function. For all the attention given in this paper to organizational capabilities, the summary at the beginning of this conclusion began with references to two things that existed outside the firm: the nature of the technology and the nature of the market. Two giant externalities remain. This is, I believe, inherent in the evolutionary theory.

As Nelson and Winter note at the outset, their theory assumes that the market performs as the neoclassical orthodoxy suggests--large numbers of consumers with access to all information make optimizing decisions [Nelson and Winter, 1982, p. 39]. I am not at all certain this assumption applies to the computer industry. Obviously, government policy affected the market for computing. Nelson and Winter are of little direct help in this regard; they explicitly dismiss from consideration situations in which government acted as a procurer [Nelson and Winter, 1982, pp. 269 and 392]. To be sure, my comparison lends some justification to their assumption; it suggests that government policies in the United States and Japan fostered the development of computing by encouraging several consumers, thus creating demand more like that envisioned by neoclassicists than one might first assume. But still, the market for computing can hardly be said to have fit the neoclassical image, especially during its early stages when the "first movers" took hold. Suppliers dealt with a few exceptionally well-informed consumers with whom they developed close relationships [Flamm, 1988]. The policies of various governments, moreover, created several distinct markets within the international economy. Though the firms I discussed were international, they did not compete in a single global marketplace for computing. The character of each firm's domestic market mattered a great deal to its performance.

My concerns about the role of the market in the evolutionary theory go beyond the matter of public policy and beyond the single case of computers. As I suggested with regard to the British case, the demand for computers was shaped not just by policy but by cultural values and consumer preferences. If all we desire as business historians is to explain why some firms failed and others prospered from within a group facing the same cultural inputs, then we might justifiably ignore those inputs. But how often can we safely assume that all firms faced the same inputs? Clearly not when we make international comparisons. But I also question whether the assumption holds even within a domestic market. In cases involving the emergence of a new technology, success often comes to those who find themselves cultivating a particular niche, either as result of previous activities or because of superior entrepreneurship. And do we want to confine ourselves to analyzing the performance of firms within industries? As historians, don't we also want to address the question of why some industries emerge and others do not?

This question brings me to the second externality--the nature of the technology. For all of the subtlety Nelson and Winter bring to the subject of technical change and for all of the attention they devote to the role of economic institutions in innovation, technology remains an independent, exogenous variable in the theory. This becomes clear in their discussion of "natural trajectories," in which they note that new technologies often give rise to regimes that follow logical patterns of development. Two common patterns or trajectories are toward economies of scale and mechanization. Generally, a body of broadly shared knowledge underlies such trajectories [Nelson and Winter, 1982, pp. 258-59].

Nelson and Winter's analysis of this phenomenon closely parallels that of Giovanni Dosi, who in a perceptive article couples the concept of natural trajectories with that of the technical paradigm. Borrowing from theories of scientific change, Dosi suggests that technology moves forward in waves, with a major breakthrough followed by a succession of modifications that move naturally toward a readily perceptible end. Like Nelson and Winter, he cites the semiconductor industry as an example [Dosi, 1982]. My study of IBM and the leading Japanese computer makers suggests that one could extend such a line of analysis to the computer industry as a whole. The recent experiences of IBM would certainly seem to lend credence to such thinking. The firm has ridden a trajectory to its logical end.

The notion of technological paradigms and trajectories raises two serious implications. First, it directs attention away from economic institutions and toward bodies of knowledge that transcend the firm. At its root, technology remains something of a black box--a matter of chance when viewed from an economic standpoint. We can try to make sense of it, but as Joel Mokyr's recent effort shows, any attempt to do so must go beyond economics and consider culture; and even then we may end up despairing of true understanding [Mokyr, 1990]. Second, it smacks of determinism. Given an adequate market, do technologies inherently drive institutions to perform certain tasks and assume certain forms [Klepper, 1992]? Nelson and Winter, like Chandler, have not escaped this question.

Ultimately, these comments about markets and technology serve to remind us that business is a vehicle, not an end in itself. IBM tells us a great deal *about* the computer revolution; it was not *itself* the revolution. Like other business institutions, IBM functioned as an intermediary between the market and technical innovation. We can learn a great deal by studying such an intermediary. At times, the vehicle itself becomes the most important element in historical change. Chandler has documented an entire epoc in American history when this was true [Chandler, 1977]. Nelson and Winter have equipped us with a powerful tool for analyzing similar situations of narrower scope. They have provided useful, if agonizing, discussions of how the intermediaries connect with the market and with the technical community and come to absorb some of those realms into themselves. But in the end, technical innovation and the market remain external and unexplained, with complex histories of their own. Perhaps inevitably, even the best theories in business history will tell us more about business than about history.

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