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Disintermediation: the Rise of the Personal Computer and the Internet in the Late Twentieth Century

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ABSTRACT

This paper is an excerpt from a larger book project called *The Corporation and the Twentieth Century*, which chronicles and interprets the institutional and economic history – the life and times, if you will – of American business in the twentieth century. This excerpt details the history of the personal computer industry and the Internet. It highlights the process of entrepreneurship and decentralized learning in these industries, and it considers the role of industrial and trade polices (in both the U. S. and Japan) in semiconductors and the development of the Internet. The excerpt ends with a consideration of *U. S. v. Microsoft* at the close of the century.

JEL: D23, F14, K21, L26, L4, L52, L63, N62, N82, O3, P12, P 14, P16
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Long before the 1960s, what was to become Silicon Valley had been built by hobbyists, tinkerers, radicals, and utopians.[1] Between the wars, the San Francisco area was a haven for amateur radio hobbyists, driven in part by the nearby naval and maritime facilities that called for and generated skills in radio. Hobbyist entrepreneurs like William Eitel, Jack McCullough, and Charles Litton went into business to produce vacuum tubes and other radio components. William Hewlett and David Packard started an electronics firm in a garage in 1938. The brothers Russell and Sigurd Varian, inventors of the klystron microwave tube, were political radicals who had grown up in a Theosophist utopian community called Halcyon. Perhaps ironically, all of these enterprises and many others thrived with defense contracts during World War II and the Korean War, turning the Peninsula into an electronics industrial district well before the arrival of William Shockley and the transistor.[2] The role of Stanford University and its enterprising provost Frederick Terman is noteworthy, even if overemphasized in popular accounts.

Although industrial districts are most certainly not a new or an isolated phenomenon, Silicon Valley holds special fascination for academics and policy analysts, some of whom claim to have discovered the secret sauce that made the Valley successful and that might do the same for other would-be Silicon Valleys around the world. Most accounts invoke the ideas of Alfred Marshall, who wrote about the ways in which a geographically concentrated but vertically decentralized industry could benefit from "external economies" analogous to the economies of scale internal to large vertically integrated firms. In the end, these external economies arise as the shared-knowledge

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1 Lécuyer (2006).

2 Leslie (1993); Wright (2020).

benefits of rapid trial-and-error learning in a decentralized setting.[3] Intimately familiar with Lancashire and the many other industrial districts in the Britain of his day, Marshall held that, in such geographic agglomerations, the "mysteries of the trade become no mysteries; but are as it were in the air, and children learn many of them unconsciously."[4]

Thus, although the voluminous wartime and Cold War flow of funds from the technostructure in Washington was crucial to Silicon Valley's takeoff, so too were many of the idiosyncratic cultural and institutional features of the Peninsula, including those inherited from the hobbyist founders. Perhaps the most significant factor in the evolution of Silicon Valley was that, unlike its counterpart in Massachusetts, it was composed largely of relatively small and independent makers of electronic components and was not dominated by integrated systems firms.[5] This provided a fertile environment for startups and spinoffs. Whereas Massachusetts law enforced non-compete clauses in employment contracts, thus raising the cost of spinning off from an employer, California law did not enforce such contracts.[6]

The work of Steven Klepper has redirected scholarly attention away from the pure Marshallian understanding of industrial districts toward the phenomenon of spinoffs, which, he showed, underpinned not only Silicon Valley but also most other industrial districts, including the early American automobile industry in Detroit.[7] Just as the

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3 Langlois and Robertson (1995, p. 114).

4 Marshall (1961 [1920], IV.x.3, p. 271).

5 Lécuyer (2006, p. 5). This does not mean, however, that it was somehow inefficient for the Route 128 region to have organized around integrated systems firms, which possessed considerable advantage in the era of the minicomputer, the region's most important high-technology product (Robertson 1995).

6 Gilson (1999).

7 Klepper (2016).

transaction costs of market exchange can sometimes make it economical to internalize transactions into a firm, so too can the transaction costs of pursuing new ideas within an existing firm sometimes impel employees to externalize their ideas to the market, especially if the institutional environment encourages the creation of new firms.[8] With the enormous potential of the transistor, there was always wide scope for new or variant approaches. Spinoffs proliferated, both because the pursuit of success with existing products in existing firms inevitably imposed constraints on divergent ideas and because employees saw the possibility of more fully appropriating the value of their ideas in the market.

In the case of Silicon Valley, the transistor-related layer that would be overlain atop the earlier industrial district of aerospace and pre-transistor technology blossomed almost entirely from a single firm: Shockley Semiconductor Laboratory.[9] As we have already seen, in 1957 eight of Shockley's employees bolted from his abrasive management style and what they considered his misdirection of product development. The traitorous eight, as Shockley is said to have branded them, set up shop as Fairchild Semiconductor Corporation. Before long, they had created the epoch-making planar process and introduced the integrated circuit. Under the direction of production manager Charlie Sporck, Fairchild began mass-producing semiconductors using approaches Sporck had

8 In both cases, these transaction costs are often what I like to call *dynamic transaction costs* (Langlois 1992b).

9 Klepper (2016, pp. 112-128).

learned at GE, employing the same kind of learning-curve pricing that Henry Ford once used with the Model T.[10]

But Sherman Fairchild had inserted a buyout clause in his contract to fund the enterprise; and in 1959 it was a no-brainer for him to exercise the option for a measly $3 million and to make Fairchild Semiconductor a wholly owned subsidiary of Fairchild Camera and Instrument.[11] As the 1960s dawned, Fairchild began its inevitable transformation into a conglomerate, acquiring 14 businesses, notably including Du Mont.[12] Almost all of these immediately began failing. Fairchild could be kept afloat only by tunneling resources away from the semiconductor division. "The Syosset folks were using large profits generated by semiconductor operations to fund acquisitions that didn't make a lot of sense," Sporck recalled.[13] "There was a growing friction between the division's management and the Fairchild corporate management." Between January and October 1965, Fairchild stock shot up from $27 a share to $144 a share; but the engineers on the West Coast had few stock options and held little of the stock.[14]

The result was the most famous, and perhaps the most significant, wave of spinoffs in corporate history. In 1967, Sporck left to reenergize a startup called National Semiconductor, turning it into a mass-production powerhouse. In a pattern that would be repeated throughout the industry, Sporck was awarded a lavish package of stock options

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[10] Lécuyer (2006, pp. 200-207).

[11] Nicholas (2019, pp. 195-196).

[12] Lécuyer (2006, pp. 259-260).

[13] Sporck (2001, p. 139).

[14] Lécuyer (2006, p. 257).

that made him a significant owner of the company. In 1969, another group of former Fairchild employees founded Advanced Micro Devices (AMD). In all, there would be 29 direct spinoffs from Fairchild – the Fairchildren – and many second- and third-generation spinoffs. A dozen of these would be among the top merchant semiconductor producers of the late twentieth century. In Klepper's view, "nearly the entire story of the semiconductor industry in Silicon Valley is about Fairchild and its descendants."[15] The most crucial defection, and the defection most devastating to Fairchild, was that of Robert Noyce and Gordon Moore in 1968. Intel, the company they founded, would rise to become the largest and most important semiconductor firm in the world. It would also catalyze the creation of a new industry in Silicon Valley: the personal computer.

By the late 1960s, the semiconductor industry was facing a crisis of complexity. Digital logic chips were being applied to an increasing variety of uses, and this implied a new hardware design for each use. In 1969, a Japanese electronics firm called Busicom approached Intel to develop the chips it needed for an electronic calculator it hoped to build.[16] Marcian E. (Ted) Hoff, Jr., the engineer in charge of the project, saw the Japanese design as too complicated. He thought the plan would result in a machine as costly and expensive as the minicomputers being made by Digital Equipment Corporation, but without the same functionality. To simplify the design, Hoff suggested creating a general-purpose chip rather than the special-purpose chips Busicom had wanted. In analogy with the digital computer – which is what in fact it was – such a chip could be programmed for a huge variety of tasks using software. The result was the Intel 4004, the first

15 Klepper (2016, p. 123).

16 Noyce and Hoff (1981).

microprocessor. In much the same way as the IBM 360, the microprocessor attacked the problem of complexity by creating a general-purpose hardware platform that could be configured to specialized uses quickly and easily with software.

By 1971, Intel had a working microprocessor. In 1974, the company introduced the 8080, capable of processing data eight bits at a time (instead of four) and addressing 64K of memory. This was to become the early standard for the microcomputer, a device that, unlike even the smallest minicomputers of the day, was cheap enough for an individual to own. The computer visionary Alan Kay dubbed such individualized machines "personal" computers.[17] Although DEC and other computer makers did begin experimenting with Intel's microprocessors, the personal computer would not emerge from existing computer firms. It would arise within the community of hobbyists.

In January 1975, the cover of *Popular Electronics* announced the Altair 8800, which it touted as the "most powerful minicomputer project ever presented – can be built for under $400." The Altair was the brainchild of Ed Roberts, whose grandly named company, Micro Instrumentation Telemetry Systems, was a storefront in Albuquerque.[18] An inveterate tinkerer, Roberts had sold oscilloscopes, remote-control devices for model airplanes, and other devices. He had entered the market for electronic calculators just as Texas Instruments was swooping in to turn that product into a commodity. Deeply in debt, Roberts persuaded a bank to lend him $65,000 on the strength of the promised cover story; and he and his team set about designing a microcomputer. The key was a volume price of

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17 Hitzlik (1999, p. xxi).

18 Freiberger and Swaine (2000, pp. 36-53). This account of the early history of the microcomputer industry generally follows Langlois (1992a).

$75 from Intel for the 8080 microprocessor. This meant that Roberts could sell the Altair kit for $379, little more than the $360 list price of the 8080. He promised the bank sales of 400 units. In the event, he was swamped with some 4,000 orders.

Once assembled, the Altair was little more than a box with lights and toggle switches. It came without software, peripherals, or even input-output devices. Many of these Roberts had promised; but, even though MITS managed to fulfill some 2,000 orders by the end of 1975, the tiny enterprise had no resources for anything but the basic kit itself. A crucial design decision would make it possible for a multitude of other small firms and hobbyists to step in to provide a wide array hardware and software compatible with the Altair. Taking inspiration from contemporary minicomputers, Roberts and his designers equipped the Altair with a number of slots into which could plug various kinds of peripherals and input-output devices. These slots were all interconnected with the microprocessor and its support chips through a system of wires called a bus. Along with the standards implied in the microprocessor itself, the bus would become one of the key interfaces of the personal computer. Indeed, the 100-wire bus of the Altair, the S-100 bus, would eventually be enshrined as the IEEE 696 bus by the Institute of Electrical and Electronics Engineers.[19]

The popularity of the S-100 standard was enhanced when the entrepreneur Bill Millard, also the founder of the ComputerLand chain of electronics stores, introduced a clone, the IMSAI 8080, first as a kit and then as a fully assembled machine. Over the

19 Noyce and Hoff (1981, p. 16).

period 1975-1978, IMSAI sold some 13,000 machines.[20] Each of them shipped with a version of the CP/M operating system, devised by a computer scientist called Gary Kildall. CP/M was able to control a 5.25-inch floppy disk drive, a technology IBM had invented in 1972 and that had become available in relatively affordably form by 1976 from an IBM spinoff called Shugart. The operating system was the third major interface of the personal computer. Because the PC was emerging from small-time outfits rather than from capable established computer companies, no single firm had anything like the wherewithal to create a complete system; a wide range of decentralized contributors had to take part. Of necessity, the PC began evolving as a relatively open modular system.[21]

The hobbyist community quickly embraced CP/M and the S-100 standard. As had happened in the early days of radio, user groups formed around the country to share information and technology. By far the most significant of these was the Homebrew Computer Club, which met most often in the auditorium at the Stanford Linear Accelerator Center, sometimes with as many as 750 people in attendance.[22] The name "Homebrew" evoked the counterculture crafts ethic, personified in the group's *de facto* leader, Lee Felsenstein, a veteran of radical politics at Berkeley. "We wanted there to be personal computers so that we could free ourselves from the constraints of institutions, whether government or corporate," said Felsenstein.[23] The personal computer should spread the way crystal radio once had, he believed, and its design should be communal. A modular

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[20] Levering, Katz, and Moskowitz (1984, p. 351).

[21] Langlois (1992a); Langlois and Robertson (1992).

[22] Freiberger and Swaine (2000, pp. 111-124).

[23] Isaacson (2014, p. 266).

system was ideal for collective innovation. A survey in January 1977 found that, of the 181 computers that members of the Homebrew Club owned, 43 were IMSAIs and 33 were Altairs.[24] Felsenstein was sure that the S-100 standard had reached critical mass; other chips and buses were doomed.

The predicted dominance never materialized. Although the hobbyists often understood themselves to be designing a computer for the people, in the main they were designing computers for hobbyists. Computers for a mass market needed to be self-contained, fully functional, and relatively easy to operate. In 1977, the nationwide electronics chain Radio Shack began selling the TRS-80 Model I. The device was built around the Zilog Z80, essentially a clone of the Intel 8080. Zilog was a spinoff from Intel, founded by Federico Fagin, a onetime Fairchild employee who had headed development of the 4004 and the 8080. Unlike the hobbyist machines, however, the Radio Shack computer used a proprietary operating system instead of CP/M. The company shipped 5,000 units by the end of the year.[25] Also in 1977, the aggressive entrepreneur Jack Tramiel introduced the Commodore PET, an all-in-one unit with the keyboard built into the case. The machine was designed by former Motorola employee Chuck Peddle, using the MOS Technology 6502 microprocessor, a clone of a Motorola chip, which Peddle had also designed. (Commodore had absorbed MOS Technology, Peddle’s spinoff from Motorola.) Like the TRS-80, the Commodore PET and its descendants sold briskly, capturing the low or “home computer” end of the market.

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[24] Moritz (1984, p. 191).

[25] L. R. Shannon, “A Decade's Progress,” *The New York Times*, September 8, 1987, p. C7.

Of course, the most significant entrant to flout the S-100 standard was Apple Computer. Steven Jobs and Stephen Wozniak were the Lennon and McCartney of the personal computer, two brilliant complements who came together in the right cultural milieu at the right time. In a far more spiritual way than Felsenstein, Jobs represented the counterculture technician – the "fusion of flower power and processor power," in the phrase of biographer Walter Isaacson.[26] The son of an engineer, Wozniak represented the techie ethos of the industrial district. "In Sunnyvale in the mid-sixties," wrote one chronicler of Apple, "electronics was like hay fever: It was in the air and the allergic caught it. In the Wozniak household the older son had a weak immune system."[27]

In early 1976, Wozniak was working as an engineer for Hewlett-Packard. Jobs did work on contract for Atari.[28] The two were college dropouts and electronics tinkerers whose previous major collaboration had been the fabrication and sale of "blue boxes" for making long-distance phone calls without charge (illegally) by imitating the audio tones AT&T used to route calls. Like most members of the Homebrew Computer Club, Wozniak wanted a computer of his own, so he set about designing what became the Apple I. Because the Intel 8080 and its variants were too expensive, Wozniak turned to Peddle's 6502, which he could get for $25 rather than about $175 for a Motorola 6800 or an Intel 8080. He wrote a version of the BASIC programming language for the 6502, then designed a computer. Instead of lights and toggles on the front panel, the machine had a keyboard and loaded from information stored on chips. It had 4K bytes of memory and could drive a black-and-

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26 Isaacson (2011, p. 57).

27 Moritz (1984, p. 29).

28 Freiberger and Swaine (2000, pp. 261-270); Moritz (1984).

white television. None of these capabilities was significant enough to draw much interest from fellow Homebrew members. But friends asked for schematics, and Jobs became convinced that he and Wozniak could make money selling the device. They scrounged together $1,300 – including by selling Jobs's Volkswagen bus – and set about assembling circuit boards in the garage at the house of Jobs's parents.

Seeing a commercial future for the microcomputer, the pair went to their employers – Atari and HP – with the idea. Both were rebuffed. "HP doesn't want to be in that kind of a market," Wozniak was told.[29] So Apple Computer formed as a partnership on April 1, 1976. As Wozniak worked to refine the design, Jobs looked to sales beyond the hobbyist market. He persuaded Paul Terrell, owner of the Byte Shop, perhaps the first computer store, to order fifty Apples. Soon they acquired funding, considerable business experience, and a new partner in Mike Markkula, a former Intel executive. Apple Computer Corporation supplanted the partnership in early 1977. Meanwhile, Jobs enlisted the Regis McKenna advertising agency to represent Apple for a share of the sales revenue.

The Apple II made its debut at the First West Coast Computer Faire in spring 1977. The machine came in a plastic case with a built-in keyboard, could be expanded from 4K to 48K of memory, drove a color monitor, connected to a cassette recorder, and featured a version of BASIC stored in a chip. Although the machine was not necessarily the hit of the Faire, Apple kept a high profile and a professional appearance quite distinct from the hobbyist firms displaying their wares. Almost immediately, sales began to take off. The company took in $750,000 in revenues by the end of fiscal 1977; almost $8 million in 1978;

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[29] Moritz (1984, p. 126).

$48 million in 1979; $117 million in 1980 (when the firm went public); $335 million in 1981; $583 million in 1982; and $983 million in 1983.[30]

In the end, what made the Apple II so successful was its compromise between technology and marketing. Under Jobs's influence, the machine was compact, attractive, and professional in appearance. Under Wozniak's influence, it was elegantly designed, easy both to use and to manufacture. Compared with earlier hobbyist machines like the Altair or the IMSAI, the Apple II was an integrated and understandable product. "My vision was to create the first fully packaged computer," Jobs told Isaacson.[31] "We were no longer aiming for the handful of hobbyists who liked to assemble their own computers, who knew how to buy transformers and keyboards. For every one of them there were a thousand people would want the machine to be ready to run." At the same time, Wozniak had prevailed upon Jobs to permit eight expansion slots. This made the Apple II in part an expandable open system that could take advantage of the crop of external suppliers that soon sprang up. An oscillating and unresolved conceptual tension between the computer as a fully finished artifact – a toaster – and the computer as an open modular system would characterize Apple throughout the era of the personal computer and beyond.

Apple relied heavily on external suppliers for almost everything. Apple president Mike Scott, who was in charge of production, did not believe in automated manufacturing and expensive test equipment. "Our business was designing, educating, and marketing. I

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30 Data from Apple Computer, cited in "John Sculley at Apple Computer (B)," Harvard Business School Case no. 9-486-002, May 1987, p. 26. Baldwin (2019, p. 19) cites IDC data that put Apple's 1983 revenues at $1.1 billion.

31 Isaacson (2011, p. 71).

thought that Apple should do the least amount of work that it could and that it should let everyone else grow faster. Let the subcontractors have the problems."[32] The company handled board-stuffing (attaching components to the circuit boards) on a putting-out system before turning to a contract board-stuffing firm in San Jose. Scott even used a contractor for the firm's payroll. In 1982, Apple was buying its floppy drives from Shugart and Alps; its hard drives from Seagate; its memory chips from Mostek, Synertek, and NEC; and its monitors from Sanyo. The components that Apple made in-house included floppy and hard-drive controllers, the power supply, and the case, all legacies of capabilities that the company developed in its earliest years. These components were assembled into finished machines in plants in California, Texas, Ireland, and Singapore.[33]

The success of the Apple II was driven in part by the transformation of the personal computer from a plaything to a tool of business. In 1979, Dan Bricklin and Bob Frankston wrote the spreadsheet program VisiCalc in Frankston's apartment in Arlington, Massachusetts. Designed for the Apple II, this was the first "killer app." By the middle of 1984, more than 700,000 copies had been sold.[34] Database programs and word processors, including the WYSIWYG (what you see is what you get) WordStar, soon appeared. By the early 1980s, the dominant design of the personal computer was becoming clear: a microprocessor unit with 64K bytes of memory; one or two floppy disk drives; and a monitor, keyboard, and printer. Multiple competing technological standards were in play, but none had become truly dominant. An attentive student of Alfred Chandler might have

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[32] Moritz (1984, pp. 200-201).

[33] Scott Mace, "Assembling Micros: They Will Sell No Apple before Its Time," *Infoworld*, March 8, 1982, p. 16.

[34] Levering, Katz, and Moskowitz (1984, p. 132).

predicted at this point that a large vertically integrated firm would emerge, either an existing large electronics firms or one arising from the ranks of the microcomputer makers, to become a dominant fast-follower and to take the microcomputer along a trajectory similar to that of the IBM 360. That did not happen.

By the late 1970s, IBM had developed an effective but highly centralized management structure in which layers of hierarchy spread beneath the all-powerful Corporate Management Committee.[35] At the same time, however, the company had created a number of relatively autonomous independent business units (IBUs) to experiment with new ideas. John Opel, soon to become IBM's president, had charged William Lowe with one of these new ideas – getting IBM into the market for personal computers. In no way did IBM view the nascent technology as a threat to its existing businesses; but customers were asking about PCs, and even some IBM staffers were playing around with them. In July 1980, Lowe met with the CMC. "The only way we can get into the personal computer business," he told IBM's top management, "is to go out and buy part of a computer company, or buy both the CPU and software from people like Apple or Atari – because we can't do this within the culture of IBM."[36] The CMC knew that Lowe was right, but they were unwilling to put the IBM name on someone else's computer. So they gave Lowe an unprecedented mandate: go out and build an IBM personal computer with complete autonomy and no interference from the IBM bureaucracy. His IBU in Boca Raton, Florida would report directly to Opel, not to the CMC. Lowe hand-picked a dozen

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35 Bresnahan, Greenstein, and Henderson (2012, p. 218).

36 Chposky and Leonsis (1988, p. 9).

engineers, and within a month they had a prototype. The committee gave Lowe a deadline of one year to market.

The timing was critical. IBM sensed that Apple and its competitors were vulnerable: they were failing to capitalize on the developing business market for personal computers. Apple was at this moment stumbling with the ill-fated Apple III, a flawed attempt at a business machine that would damage the company's reputation. But for IBM to get a PC to market quickly meant bypassing the company's cumbersome system of bureaucratic checks and its heavy dependence on internal sourcing. Philip Donald Estridge, who succeeded Lowe as director of the project, put it this way. "We were allowed to develop like a startup company. IBM acted as a venture capitalist. It gave us management guidance, money, and allowed us to operate on our own."[37] Estridge knew that, to meet the deadline, he would have to design a machine that was not at the cutting edge of technology. Moreover, IBM would have to make heavy use of outside vendors for parts and software. The owner of an Apple II, Estridge was also impressed by the importance of expandability and an open architecture. He insisted that his designers use a modular bus system, based on the S-100, that would allow expandability, and he resisted all suggestions that the IBM team design any of its own add-ons. As Carliss Baldwin notes, the "IBM PC was the first computer platform that was open by choice and not because of financial constraints."[38]

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37 "How the PC Project Changed the Way IBM Thinks," *Business Week*, October 3, 1983, p. 86.

38 Baldwin (2019, p. 2).

The only part of the IBM PC implying anything like a technical advance was the choice of the Intel 8088 microprocessor. Although touted as a 16-bit chip, and thus an advance over the 8-bit 8080, the 8088 processed data internally in 16-bit words but used 8-bit external buses.[39] The IBM team decided against the 8086, a full 16-bit chip, because they feared its power would raise the hackles of turf-protectors elsewhere in the company.[40] Moreover, the 8088 was perhaps the only 16-bit microprocessor for which there already existed a full complement of support chips. Choosing the 8088 microprocessor meant, however, that the IBM PC could not use existing operating systems designed for 8-bit chips. Here again, IBM chose not to write its own proprietary system but to go on the market. Estridge's group approached Gary Kildall, who was working on a 16-bit version of CP/M. But IBM and Kildall were initially unable to come to terms.[41] So IBM turned instead to Microsoft, a small Seattle software firm that had gotten its start writing a version of the BASIC language for the Altair.

Bill Gates, the company's co-founder, jumped at the chance to supply a key piece of software to IBM. Microsoft bought an operating system for the 8088 from a local Seattle software house, put the finishing touches on it, and sold it to IBM for a lump-sum fee as MS-DOS (Microsoft disk operating system). IBM called its version PC-DOS, but, at the insistence of Gates, it allowed Microsoft to license MS-DOS to other computer makers. In the end, three operating systems were available for the IBM PC, including a 16-bit version of CP/M; but PC-DOS was the only operating system initially available, and IBM priced

39 Noyce and Hoff (1981, p. 15).

40 Chposky and Leonsis (1988, p. 24).

41 Chposky and Leonsis (1988, pp. 43-53); Freiberger and Swaine (2000, pp. 330-337).

it at only $60, one-third the price of the cheapest alternative.[42] "We wanted the same kind of forces that were putting VHS cassettes into every video store to push MS-DOS to become the standard," said Gates.[43]

Shunning IBM's staff of commission sales agents, the PC group turned to retail outlets Sears and ComputerLand to handle the new machine. Perhaps the most striking way in which IBM relied on external capabilities, however, was in the actual fabrication of the PC. All parts were put up for competitive bids from outside suppliers. When internal IBM divisions complained, Estridge told them to their astonishment that they could submit bids like anyone else. With a little prodding, some IBM divisions did win contracts. The Charlotte, North Carolina, plant won a contract for board assembly, and the Lexington, Kentucky, plant made the keyboard. But when an IBM plant in Colorado could not make quality disk drives, Estridge turned to Tandon as the principal supplier. Zenith made the PC's power supply, SCI Systems stuffed the circuit boards, and Epson made the printer.[44] The machine was assembled from these components on an automated line at Boca Raton that in 1983 could churn out a PC every 45 seconds.[45]

The IBM PC was an instant success, exceeding sales forecasts by some 500 percent. The company shipped a mere 13,533 machines in the last four months of 1981, an amount far behind demand. Order backlogs became intolerable.[46] But by 1983, the PC had

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42 Scott Mace, "IBM Releases CP/M-86 for the Personal Computer after Delay," *InfoWorld*, April 26, 1982, p. 8.

43 Gates (1995, p. 48).

44 Chposky and Leonsis (1988, pp. 88, 68).

45 "Personal Computers: And the Winner Is IBM," *Business Week*, October 3, 1983, p. 78.

46 Chposky and Leonsis (1988, p. 24).

captured 26 per cent of the market. In 1983, IBM earned revenues of $2.7 billion on sales of 670,000 units, besting Apple's 640,000 units.[47]

In the early 1980s, IBM had indeed stepped in to place the *imprimatur* of the large vertically integrated corporation on what had been an amateurish, hobbyist-driven industry. But it did not do so by using its own internal capabilities. It had created a product built of parts widely available in the market. In the beginning, a gleaming and peerless brand name, along with the logistics and assembly capabilities at Boca Raton, made it possible for IBM to earn rents from the PC. And one could imagine IBM continuing to dominate the PC market, albeit with a business model very unlike that of its traditional product lines. Yet even such an un-Chandlerian form of dominance would not happen. A raft of makers of clone computers immediately arose, almost all of them startups. By 1988, they had effectively wrested control of the IBM PC away from IBM.

A modular system "externalizes" economies of scope.[48] That means, in effect, that there is no way in such a system to earn rents from arranging the parts in a superior way. The system architecture and technological standards determine how the parts go together, and the market for most parts is highly competitive. The only way to earn rents in a modular system is to control a component that is a *bottleneck*, which Baldwin defines as "a critical part of a technical system that has no – or very poor – alternatives at the present time."[49] In the case of the personal computer, as we have seen, there are three potential bottlenecks: the bus, the microprocessor, and the operating system. Because IBM could

47 IDC, cited in Baldwin (2019, p. 19).

48 Langlois and Robertson (1992).

49 Baldwin (2018, p. 3).

not imagine that the PC would ever challenge its core business, it gave Microsoft free rein with the operating system.[50] The company insisted on second-sourcing for the microprocessor to limit Intel's control of that bottleneck. Although it would have been impossible to copyright the bus itself, which was essentially stolen from the S-100, IBM did attempt to control the computer's basic input-output system (BIOS) by publishing, and thus copyrighting, its design. IBM prosecuted the first wave of clones successfully; but, beginning with the Texas-based startup Compaq, the clones soon learned to reverse-engineer the BIOS in a way that didn't infringe copyright. By the middle of 1985, IBM's market share began plummeting while that of the clones took off.[51] Already in 1986, more than half of the IBM-compatible computers sold did not have IBM logos on them.

The open modular architecture of the PC unleashed intense competition in the assembly of the machines and the invention and production of complementary parts and software. Americans welcomed the new device with enthusiasm. In 1984, some eight per cent of households possessed a computer; by 1993, 23 per cent did.[52] At the turn of the millennium, more than half of American households owned a personal computer, and more than half of all employees used a PC at work.[53] In 1975, some 10,000 microcomputers were shipped; in 1980, the number was almost 800,000; and in 1990, the figure was seven

[50] Gerstner (2002, pp. 110-120).

[51] Baldwin (2019, p. 20).

[52] U. S. Bureau of the Census, Current Population Survey, various years. Today far more than 90 per cent own a computer, although that term has been defined – as it should be – to include smartphones and tablets.

[53] Bureau of Labor Statistics, U. S. Department of Labor, *The Economics Daily*, Computer use at work in 2003, available at https://www.bls.gov/opub/ted/2005/aug/wk1/art03.htm (visited June 8, 2021).

million.[54] In the year 2000, 44 million PCs were shipped in the U. S. and 134 million worldwide.[55] The 1970s and early 1980s – years so devastating to much of American industry – had incubated a wholly new industrial sector. That sector would soon disrupt the existing American computer industry, although, as we will see, it was a disruption that was already underway even before the maturity of the personal computer. At the same time, however, the personal computer would ride to the rescue of the firm and the industry that had given it birth: Intel and the American semiconductor industry.

As we saw at great length, in the 1970 and 1980s American firms in traditional industries, notably automobiles and consumer electronics, were succumbing to competition from the inexpensive, innovative, and well-made products of Japan. The consumer-electronics industry was all but destroyed. But the genuine existential threat was not to old-line industries like cars and TV sets. Japan was also threatening to take over the semiconductor industry, which represented not America's industrial past but its hoped-for future. In 1986, Japan's worldwide share of the merchant semiconductor market surpassed that of the U. S.[56] Worse, Japanese market share was on the ascent and American share on the decline. Surely the demise of semiconductors would bring in its wake a cascading fall of downstream high-tech industries, including computers.

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54 Computer and Business Equipment Manufacturers Association, *1992 Information Technology Industry Data Book*, p. 94.

55 Matt Hamblen, "Update: PC Market Declines in 2001; Slow Turnaround Expected," *Computerworld*, January 18, 2002.

56 Merchant semiconductor firms are those that sell into the market rather than producing for their own consumption. In fact, some 30 per cent of American production in 1986 was captive, most of that internal production by IBM, by far the largest producer of semiconductors in the world at the time. If captive production is counted, U. S. production was some 30 per cent higher than Japanese production in 1986 (Langlois, Pugel, Haklisch, Nelson and Egelhoff 1988, p. 27).

For many observers, the source of America's developing weakness was its fragmented structure.[57] In the capital-intensive business of semiconductor fabrication, vertically disintegrated American firms did not have the cash reserves to weather industrial downturns, so investment was highly cyclical. By contrast, Japanese producers could rely on their *keiretsu* to tunnel resources and smooth investment. Moreover, all were sure, Japanese industry benefitted from the comprehensive planning and cooperative research that MITI provided. This view was echoed by the prestigious MIT Commission on Industrial Productivity, which declared in 1989 that "the traditional structure and institutions of the U. S. industry appear to be inappropriate for the challenge of the much stronger and better-organized Japanese competition."[58] The commission pronounced the American merchant sector "too fragmented" and called for consolidation and rationalization. The cognoscenti agreed that the problem with the American semiconductor industry was … Silicon Valley.

In 1989, the very year in which the MIT report emerged, a dramatic reversal of fortune began. American market share rose above 50 per cent, where it has remained ever since.[59] Japanese market share entered secular decline. Today, Japan has something like 10 per cent of the market for semiconductors, half the share of Korea. What happened?

When Intel introduced the microprocessor in 1969, logic chips were actually something of a side hustle. Intel's business was memory. As the planar processor allowed

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57 Borrus (1988); Ferguson (1988); Prestowitz (1988).

58 MIT Commission (1989, p. 20).

59 Semiconductor Industry Association 2021 Factbook, p. 3. Available at https://www.semiconductors.org/resources/factbook/.

more and more transistors to crowd cheaply onto a chip, it became economical to use integrated circuits to replace bulky ferrite cores for computer memory. IBM developed the technology inhouse. Not wanting to fall behind, Burroughs put out a call to Silicon Valley.[60] Intel won the contract, producing the 1103, a 512-bit dynamic random-access memory (DRAM) chip, in October 1970. A 1,024-bit design for Honeywell soon followed. By 1972, Intel's DRAM was the largest-selling semiconductor product in the world, accounting for more than 90 per cent of the company's revenue.[61]

Before 1975, Japan restricted imports of semiconductors, often with prior-approval requirements, and essentially forbade foreign direct investment.[62] As it had in other sectors, MITI wanted consolidation; but, as in other sectors, the firms themselves resisted, and there remained more than six major competitors despite the policy of NTT, the state telephone monopoly, to buy only from a chosen four. With no military demand and a focus on consumer products, the Japanese semiconductor firms were late in making the transition to silicon, and they found it hard to compete with the likes of TI and National in the 1960s. Some Japanese firms accused the Americans of dumping. By the late 1960s, the Japanese semiconductor firms realized that they needed to adopt the strategy that had worked so well for Japanese firms in other sectors. They would compete through high-quality manufacturing rather than product innovation. And they would enter the American market

60 Lécuyer (2006, p. 282).

61 Burgelman (1994, p. 33).

62 Irwin (1996, p. 28). Both the U. S. and Japan had tariffs on imported semiconductors. These were reduced in 1978 and ultimately eliminated in 1985.

by specializing in a single product, expanding to other products only once they had established themselves. The product they chose was the DRAM.

As the first mover, Intel needed to invent process technology as it went along. (This indeed was the company's philosophy of R&D, what Noyce called the principle of "minimum information" – do research only when you run into a roadblock and have no other choice).[63] The company saw its core competence as the integration of technology development with manufacturing, which typically meant carrying out development directly on the production line.[64] By the 4K generation in 1972, however, Intel's DRAM was becoming a dominant design, and new generations were falling into step in predictable cycles. This shifted advantage away from innovative Intel to firms focused more keenly on mass production. Development on the production line itself fell in importance as specialized equipment makers became significant sources of innovation.[65] The large Japanese manufacturers like Fujitsu, NEC, and Hitachi built relationships with Japanese equipment makers, notably Nikon and Canon, whose capabilities in photography could be adapted to the important process of photolithography. Along this dimension, the Japanese DRAM makers were *more* vertically specialized than Intel, not less.

As DRAM generation succeeded generation, Intel and other American firms began to stumble. In contrast to the conservative approach of the Japanese, the American firms insisted on radically new designs and new process technology, which lengthened

63 Moore and Davis (2004, p. 20).

64 Burgelman (1994, pp. 32-34).

65 Pillai (2020).

development times and increased start-up problems.[66] By the 64K and 256K generations, Fujitsu and Hitachi were beating Intel to market, in a period during which the dollar was appreciating against the yen. Whereas American firms were experiencing yields (the fraction of chips produced that actually worked) of 50 to 60 per cent, Japanese firms were achieving 70 to 80 per cent.[67] Hewlett-Packard discovered that the failure rate of Japanese-made chips was one-fifth that of American-made ones. Already by the 16K generation, Japanese firms had 41 per cent of the market for DRAMs.[68] By the 256K generation, the figure was 92 per cent; and by the 4M generation in 1985, Japanese firms had 98 per cent of the market. Even though DRAMs represented only seven per cent of the semiconductor market in 1985, the loss of that market seemed especially catastrophic because the mass-produced DRAM was considered to be a technology driver – its manufacture generated knowledge spillovers that were important for the fabrication of all other kinds of chips.[69]

Japanese success in semiconductors was widely understood to have been the product of massive government funding and cooperative research orchestrated by MITI. In reality such funding was modest, an order of magnitude less than the defense-related funding American firms had been receiving.[70] As with much of industrial policy in electronics around the world (including the U. S.) in this period, the Japanese VLSI (very-

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66 Borrus (1988, p. 144).

67 Prestowitz (1988, pp. 146, 135-136).

68 Dataquest, cited in Methé (1991, p. 69).

69 Irwin (1996, p. 15); Irwin and Klenow (1994).

70 Irwin (1996, p. 42).

large-scale integrated circuit) program was prompted by fears of IBM dominance.[71] Japanese officials believed that the only way to compete with IBM in mainframe computers was to bolster national capabilities in semiconductors. Over the period 1975 to 1981, NTT sponsored some $180 million worth of research in its own labs to benefit its four favored suppliers.[72] Because this left out major companies like Toshiba and Mitsubishi, MITI created the VLSI program in 1976 with about $130 million in subsidies for cooperative research. As had been the case in other industries, the companies were happy with the subsidies but strongly resisted any attempts at planning and coordination by MITI. As a result, some 85 per cent of the subsidies went to the private company laboratories not the joint lab MITI set up.[73] When MITI set 256K devices a planning goal, it came as an embarrassment that Matsushita, a firm with no connection to the project, had already developed a 1M DRAM on its own.[74] In the end, much of the MITI-funded research focused on what turned out to be a dead-end: high-energy alternatives to photolithography, which even today have not supplanted optical techniques.[75]

Already by 1981, Robert Noyce of Intel, Charlie Sporck of National, and Jerry Sanders of AMD were making the rounds in Washington under the aegis of the recently created Semiconductor Industry Association.[76] They found little purchase at first. But

71 Japan would indeed be successful in developing a computer industry to rival IBM – just in time for the "competitive crash" of the mainframe and minicomputer industries that, as we will soon see, would throw IBM itself into crisis.

72 Callon (1995, p. 37).

73 Fransman (1990, p. 80).

74 Sigurdson (1986, p. 53).

75 Callon (1995, p. 119); Sigurdson (1986, p. 83).

76 Prestowitz (1988, pp. 148-161).

after the boom in personal computer sales in 1983, the PC market cooled and semiconductor demand fell, especially for memory chips. Merchant semiconductor firms all started losing money; and the industry turned more seriously to Washington for help. In June 1985, Micron, a small Idaho firm specialized in DRAMs, filed an antidumping petition with the ITC against four Japanese firms in the market for 64K memory. In September, Intel, National, and AMD filed against Fujitsu, Hitachi, and Mitsubishi in the market for a different kind of chip. In the hopes of heading off Congressional action, Ronald Reagan placed commerce secretary Malcolm Baldrige in charge of a "strike force" against unfair trade practices. The commerce department thereupon took the unprecedented move of filing its own unsolicited antidumping case in the market for 256K and future generations of DRAMs.

In a replay of the crisis in automobiles a few years earlier, the Reagan administration found itself forced to negotiate voluntary export restraints with Japan, what would become the Semiconductor Trade Arrangement.[77] The commerce department began to promulgate firm-specific price floors. But MITI found the agreement vague and difficult to administer, especially as low-price chips began leaking into the U. S. from third countries, sometimes supposedly smuggled in from Mexico and Canada in the trunks of cars. In 1987, under Congressional pressure – instigated by the delegation from California – Reagan imposed 100 per cent tariffs on $300 million worth of goods imported from Japan. The sanctions dramatically enhanced MITI's sway over the companies. As had happened in automobiles, the voluntary restraints cartelized the Japanese industry,

[77] Flamm (1996, pp. 159-226); Irwin (1996).

generating rents that the Japanese firms plowed back into R&D and the development of higher-value products. In 1988, chip prices that had been falling at rates as high as 60 per cent a year suddenly *increased* by well over 20 per cent.[78] American computer makers protested the increase in chip prices, to little avail. The Arrangement would remain in place through 1991.

The other major political response to the crisis of 1985 was an attempt to imitate the cooperative research efforts of Japan. Like the state department, the defense department was cool to trade restrictions against Japan: defense procurement relied on many Japanese-made products, and Japan was a key American ally in the Far East.[79] But in 1987, the Defense Science Board, a DOD advisory committee, issued a report alarmed about the state of the "defense industrial base."[80] Because commercial uses of semiconductors now swamped military uses – meaning that technological change was "spinning on" to defense uses instead of "spinning off" from them – the defense department had a stake in assuring the health of the commercial sector. The SIA issued a plan for a research consortium of 14 major firms, representing 80 per cent of American semiconductor capacity.[81] The military agreed to match funds for the consortium, channeling $100 million a year through the Defense Advanced Research Projects Agency to help underwrite what would be called Sematech.

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78 Flamm (1996, p. 240).

79 Irwin (1996, pp. 38-39). DOD was also generally liberal on trade issues because its client defense contractors tended to be export oriented.

80 Grindley, Mowery, and Silverman (1994).

81 In 1984, Congress had passed the National Cooperative Research Act, which limited antitrust liability for research joint ventures.

With Noyce as its president, Sematech set up an experimental production facility in Austin, Texas. As had happened in Japan, however, the manufacturing firms resisted genuine cooperative research, which potentially threatened individual competitive advantages. The consortium's mission quickly changed from "horizontal" cooperation among producers to "vertical" cooperation with the makers of semiconductor manufacturing equipment. Although dominated by a single large firm – Applied Materials, often called the IBM of the semiconductor-equipment industry – the tool suppliers were highly fragmented into hundreds of small, specialized firms.[82] Sematech arguably helped build capabilities in that industry and foster cooperation between suppliers and manufacturers. DARPA support ended after five years and a total of $500 million. Sematech soon began accepting non-American members and evolved into a generic trade institute for the semiconductor industry.

Whether the benefits of Sematech outweighed its costs remains an open question. Large manufacturers like Intel were already beginning to work closely with the tool suppliers. American manufacturing equipment sold well in Japan, suggesting that Japanese firms also benefited from improved capabilities in that sector. And one study found that R&D at Sematech displaced $300 million of R&D that would have taken place privately.[83] What is clear is that Sematech played at best a small role in the resurgence of the American semiconductor industry in the late 1980s. That resurgence was driven by two factors: an increased focus on quality in American manufacturing facilities (fabs) and a structural shift away from memory chips toward the microprocessors and other logic chips that were being

[82] Langlois (2006).

[83] Irwin and Klenow (1996).

absorbed by the rapidly expanding personal-computer industry.[84] Intel was at the center of both developments.

By the mid-1980s, the managers of American semiconductors firms, in many cases founder-owners, recognized that to survive they would need to emulate Japanese manufacturing practices. And in firms younger and far more nimble than those of America's traditional industries, the semiconductor makers were able to accomplish that feat. (As Margaret O'Mara put it, the firms of Silicon Valley "blended the organizational chart of the twentieth-century corporation with the personal sensibilities of the nineteenth-century sole proprietorship.")[85] Motorola and TI, both of which had operations in Japan (antedating the prohibitions on FDI), were the first to begin applying Japanese manufacturing practices, but Intel and other American firms were not far behind.[86] The American companies innovated in ways that improved the techniques they were learning from Japan. Intel broke development down into modules, allowing intense experimentation at the level of pilot production without having to worry about the complex interdependencies of the entire system. These modules could then be scaled up to the production level, usually at multiple fabs, by precise duplication – the "copy exactly" methodology – to avoid adding unforeseen interdependencies. Costs declined; and by the early 1990s, the defect rates of American chips were as low as those from Japan.

While still at Fairchild in the early 1960s, Gordon Moore had already formulated what would become one of the most significant ideas in the history of manufacturing:

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84 Langlois and Steinmueller (1999).

85 O'Mara (2019, p. 106).

86 Macher, Mowery, and Hodges (1998); Lécuyer (2019).

Moore's Law.[87] But it was in the mid-1980s that the idea took form – that the number of transistors on an integrated circuit should and will continue to double every eighteen months – and became a roadmap that Intel and other American firms could use to drive and coordinate technological change in the industry.[88]

The fortunes of the American semiconductor industry were also bolstered by internationalization. Thanks to the development of computerized design tools and the standardization of manufacturing technology, new firms could enter the industry by specializing in the design phase of semiconductor production, outsourcing the actual manufacturing to "silicon foundries" that were popping up, especially in Asia outside of Japan. The vast majority of these "fabless" semiconductor firms were based in the U. S. to take advantage of American design capabilities and to be close to customers. The Semiconductor Chip Protection Act of 1984 created property rights in modules of reusable design components or "intellectual property blocks" that could be traded on markets, further spurring specialization in chip design.[89]

This same internationalization began wreaking havoc on the Japanese. Manufacturing DRAMs cheaply as an entree to the chipmaking industry was a strategy that other countries, especially other Asian countries, found easy to imitate. The high prices created by the voluntary export restraints encouraged massive investments in DRAM production by Korean firms, just as the Japanese yen was appreciating on international

87 Gordon Moore, "Cramming more Components onto Integrated Circuits," *Electronics*, April 19, 1965.

88 Lécuyer (2020).

89 Macher, Mowery, and Hodges (1998, p. 127).

markets.[90] In 1991, Samsung was the largest producer of 1M DRAMs in the world. By the end of the century, Japanese chip makers would be accusing the Koreans of dumping.[91] In the end, the American industry benefited little from the Semiconductor Trade Arrangement. American firms didn't reenter the DRAM market, though Micron, the only remaining American firm to produce DRAMs on American soil, did prosper; today it is the third-largest producer, trailing only two Korean firms. The main driver of the American resurgence was the industry's shift away from memory and other "commoditized" semiconductors in favor of high-margin design-intensive chips.[92] For such chips, production costs are not the sole dimension of competition: innovation and responsiveness to users count importantly. And innovation and responsiveness were the strong suit of the "fragmented" American industry, with its capabilities in design and close ties to the burgeoning personal computer industry. This shift was well underway before the STA and would have proceeded without it.

Foremost among the products to which the American industry turned was the microprocessor. Already by 1983, Intel had contemplated exiting the failing DRAM business.[93] Top executives including Noyce and Moore found it difficult to move away from what they saw as the company's core competence and technology driver. "It was kind of like Ford deciding to get out of cars," said one executive. But company president Andrew Grove was less sentimental, and already by fall 1984 he and board chair Gordon

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90 Flamm (1996, p. 435). In early 1985, it took 260 yen to buy a dollar. In 1988, it took half that.

91 Kuriko Miyake, "Japanese Chip Makers Suspect Dumping by Korean Firms," *Computerworld*, October 24, 2001.

92 Langlois and Steinmueller (1999).

93 Burgelman (1994).

Moore had agreed not to proceed with the 1M DRAM. By the next summer, they had implemented what Grove saw as "internal creative destruction," reorienting the company toward the microprocessor. This included some $250 million investment in design talent and computer-aided-design tools. The rapid growth of the personal computer industry – something not foreseen when the decision to bet on the microprocessor was made – catapulted Intel to the top of the semiconductor industry. In 1994, it was the largest IC producer in the world, its nearly $10 billion in revenue $1 billion more that the next largest producer (NEC). The story of the American resurgence in semiconductors is basically the story of the resurgence of Intel.

Crucial to Intel's success was the company's decision to stop licensing its microprocessor designs to other manufacturers. Second-sourcing had helped expand markets in the early days, the company felt, but in the end "we lost control over a generation of our products and created our own competition."[94] Computer makers liked multiple-sourcing because it insured them against disruptions in production. But as it grew, Intel was producing at multiple plants using its copy-exactly approach, in effect providing multiple-sourcing internally.[95] After Intel successfully sued NEC for copyright infringement, the company's only serious competitor in Intel-compatible microprocessors would be AMD, which, in a series of complex and much-litigated moves, continued to produce chips that emulated the Intel standard. By the late 1980s, Intel, with some

94 Intel Corporation Annual Report 1986, p. 2

95 Lécuyer (2019, p. 370).

competition from AMD, was effectively in control of one key bottleneck in PC design just as Microsoft was in control of another. The IBM-compatible PC became the Wintel PC.

Competition from alternative PC standards had essentially dwindled to one. Even as it edged into what was only a market niche, Apple would create the prototype of what all personal computing would soon look like. In December 1979, Steve Jobs paid a reluctant visit to the Xerox Palo Alto Research Center as part of deal to attract investment from the giant copy-machine company.[96] In one of the most famous episodes in the history of computing, Jobs was introduced to bitmapped graphics, overlapping windows, and a pointing control device called a mouse, which had been invented a decade earlier by Douglas Engelbart and his team at SRI International. Jobs went back to Apple and incorporated much of what he saw into a computer called the Lisa, which appeared in January 1983. The Lisa was expensive ($10,000), slow, and lacked software; it was not in fact much more of a success commercially than the disastrous Apple III. But it set Apple on a new strategic course emphasizing design elegance and ease of use.

In January 1984, Apple introduced the Macintosh with what is perhaps the most iconic television commercial of all time, shown during Superbowl XVIII.[97] Set in what is obviously a dystopian world, the ad depicts an athletic young woman suddenly launching a sledgehammer into the screen from which an outsized Big Brother is intoning collectivist tropes to an audience of colorless drones. Because of the soon-to-be-released Mac, the ad assured us, 1984 wouldn't be like *1984*. Of course, all understood that Big Brother was

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96 Isaacson (2011, pp. 94-101); Hiltzik (1999, pp. 329-345).

97 Isaacson (2011, pp. 164-165).

IBM. Amusingly, however, IBM's own ad campaign had moved along similar lines. The company's mute PC spokesman had been a whimsically reincarnated version of Charlie Chaplin's Little Tramp character, who discovers that, far from enmeshing him in the diabolical gears of *Modern Times*, the IBM PC was making his life easier.

The Macintosh was a less-expensive machine that retained many of the Lisa's advanced features. It came in a minimalist plastic case with built-in screen and featured both a mouse and a graphical user interface. The Mac did not come close to overthrowing the IBM-Wintel standard, but it found its place where its graphical capabilities were important, notably desktop publishing. Part of what made the Mac attractive was the unity and simplicity of its design. This reflected the ascendancy of Jobs over Wozniak, of design over open modular systems. As Jef Raskin, the original Mac project director, put it, "Apple II is a system. Macintosh is an appliance."[98] The non-systemic character of the Apple III, Lisa, and Macintosh machines was simply a reflection of the fact that they were bounded in conception by a single mind: that of Jobs. His approach was visionary, personal, and aesthetic. He wanted to design the ideal machine that he would himself like to own. His demand for centralized control extended to manufacture. Unlike the Apple II, the Mac would be made at Apple's own highly automated assembly facility, which would emulate Fordist principles and Japanese manufacturing techniques – in Fremont, not far from where NUMMI was at the same moment cranking out Chevy Novas.[99] Because the Macintosh never achieved the sales Apple had hoped for, the Fremont plant ran at low capacity and

98 Moritz (1984, p. 130).

99 John Markoff, "Apple Computers Used to Be Built in the U.S. It Was a Mess," *The New York Times*, December 15, 2018.

high cost. For his part, Wozniak railed against what he considered the company's proprietary attitude, and by 1985 he had left Apple.

The great counterfactual question of the early personal-computer industry is this: why did IBM allow Intel and Microsoft to control the major bottlenecks of the PC standard? Some have suggested that IBM did not prevent Microsoft from licensing MS-DOS to others because it was cowed by the antitrust suit then still in play. Indeed, some have credited the antitrust suit with the whole of IBM's failure to have dominated the PC market.[100] The evidence decisively demonstrates otherwise. Indeed, even asking the question reads history backwards. In 1980, apart from a few visionaries, no one, least of all IBM, had an inkling that the personal computer would become as important as it did. The group in Boca Raton was concerned with getting out the door quickly what they saw as a trifling addition to IBM's product line. Although IBM had demanded second-sourcing of the 8088 microprocessor, by the time Intel stopped second-sourcing in 1985, IBM was more concerned with bolstering Intel's fortunes than in limiting its market power: in late 1982, IBM had bought $250 million worth of Intel stock – 12 per cent of the company – to make sure the chipmaker stayed afloat.[101]

One could imagine that, even without the ability to control any bottlenecks, IBM might have retained its dominance on the strength of its brand name and logistics capabilities. At the end of the century, another computer firm – Dell – would do just that.

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100 I most recently heard this claim voiced by a distinguished Ivy League historian at an international conference in 2019.

101 Andrew Pollock, "In Unusual Step, I.B.M. Buys Stake in Big Supplier of Parts," *The New York Times*, December 23, 1982, p. A1. In 1982, Intel was still supplying chips for IBM's larger computers not just the PC.

But the IBM Corporation was fundamentally ill designed to manage a technological system over which it did not have proprietary control.[102] In April 1987, IBM announced its PS/2 line of computers. Although attractive and functional, the new machines featured a proprietary bus called the Micro Channel Architecture, which was not backward compatible with all older software. Buyers preferred the older standard and stayed away from the new PS/2 machines in droves. IBM was ultimately forced to abandon the MCA. In 1988, with some nudges from Intel and Microsoft, nine of the major clone makers banded together to announce development of a competing 32-bit bus called the Extended Industry Standard Architecture. This, and not the MCA bus, quickly became the standard for the personal computer.

It is an interesting theoretical question: why can't a corporate division do anything a freestanding firm could do? IBM gave the Boca Raton IBU almost compete autonomy, and it behaved in the beginning much like an independent startup. The answer is that ownership structure changes incentives.[103] For its larger computers, IBM enjoyed tremendous internal economies of scope among its divisions. Not only did the PC not share in those economies, it could even damage them – as when Boca Raton produced the inferior IBM PCjr home computer, which many felt threatened the company's overall brand-name capital. As the PC became more powerful, the other IBM divisions insisted that the smaller machine be made to fit in with the company's traditional strategy for information processing. This is the actual origin of the MCA bus, which was designed to facilitate future compatibility with larger computers rather than to serve the needs of the PC

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[102] Langlois (1997).

[103] Williamson (1985, chapter 6).

customer.[104] In the end, for fundamentally structural reasons, IBM failed to understand the nature of standard setting in the PC industry, and it attempted to take the PC proprietary without first controlling the standard.

Already in 1983, the PC division had been renamed the Entry Systems Division and had lost its direct report to Opel. In early 1985, the ESD was pulled completely back within the structure of the company, its autonomy gone. IBM began developing a proprietary operating system, eventually to be called OS/2, for its PCs and other entry-level machines. Although Compaq and other clone makers had already moved on to the Intel 80386 chip, IBM chose to design OS/2 specifically for the 80286 chip then still widely in use. This it did in its time-honored mainframe fashion, deploying some 1,700 programmers in multiple sites on four continents.[105] The company poured hundreds of millions into what would be a slow and bloated piece of software. OS/2 was initially to have been developed in cooperation with Microsoft; but Gates, with a far better understanding of the PC market, soon maneuvered away from OS/2 to his own Windows software, which created a Mac-like graphical user interface sitting on top of MS-DOS.[106] IBM remained a minor player in personal computers until, after losing billions in the early 2000s, it sold its PC division to the Chinese firm Lenovo. Of course, by then IBM was a very different company.

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104 Bresnahan, Greenstein, and Henderson (2012).

105 Carroll (1993, p. 109).

106 Windows 95, the first version of the software to offer a genuine challenge to the Mac, was not merely a GUI on top of MS-DOS, but it still relied heavily on MS-DOS code. In the early 1990s, after the personal computer had begun destroying the minicomputer industry, Microsoft hired engineers from DEC (and from the failing IBM OS/2 project) to rewrite Windows from scratch and sever its connection to MS-DOS (Zachary 1994). The result was Windows NT, which became the basis of twenty-first-century versions of Windows. Microsoft spent $150 million on the project, but was careful to give the design team free rein without corporate interference.

In 1957, Ken Olsen and Harlan Anderson, two MIT graduates working at MIT's Lincoln Labs, secured funding from the American Research and Development Corporation, the seminal venture-capital firm founded by General Georges Doriot.[107] Soon to be called the Digital Equipment Corporation, their venture focused on the minicomputer, a machine that was smaller and cheaper than a mainframe and was aimed at scientific and technical uses. By 1965, the company was mass producing the PDP-8, which sold for a mere $18,000. As DEC employees spun off competing and complementary firms, a rich ecosystem of minicomputer makers evolved along Route 128 outside Boston. Consciously and unconsciously, the minicomputer makers kept to their own niche and avoided confrontation with IBM.

In 1966, DEC introduced the PDP-10, which became the workhorse of timesharing, a system in which multiple users could remotely access the same computer simultaneously. To use somewhat anachronistic lingo, timesharing was originally a system of "dumb" clients, teletype machines or cathode-ray terminals, connected to a "smart" server, a mainframe or minicomputer. With the relentless progress of Moore's Law, smaller machines began to challenge the minicomputer for the scientific and engineering segment. Sun Microsystems came to lead the market for workstations – essentially personal computers with hopped-up microprocessors and co-processors – by consciously employing a radically open and modular strategy.[108] In due course, the Wintel personal computer would come for the workstation.

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[107] Nicholas (2019, pp. 127-131); Rifkin and Harrar (1988).

[108] Baldwin and Clark (1997); Garud and Kumaraswamy (1993).

The ascendancy of cheap, powerful, individualized computers changed the economic geography of the client-server relationship. Clients became smart, as smart indeed as even some contemporary servers; and it no longer made sense to connect clients to distant computers, especially over relatively slow and low-quality phone lines, in order to run applications software. Financial markets anticipated this altered economic geography even before the underlying technology had actually changed, leading to what Tim Bresnahan and Shane Greenstein called the "competitive crash" of the computing industry in the early 1990s.[109] As submarkets that had evolved separately – mainframes, minicomputers, workstations, and PCs – began to intersect, rents were suddenly and dramatically reallocated across segments.

By 1998, the pieces of DEC, once the second-largest computer company in the world, were being sold off to the likes of Intel and the onetime clone-maker Compaq, which would itself soon be absorbed by Hewlett-Packard, the only old-line electronics firm to show consistent success in the personal-computer industry. IBM too was in crisis. In 1993, a year in which it lost $8 billion, the company broke with tradition and hired an outside CEO. A former American Express executive, Lou Gerstner had been KKR's choice to head RJR Nabisco after the epic hostile takeover.[110] Fighting strong opposition, Gerstner set about completely reengineering IBM, selling off money-losing hardware businesses and focusing increasingly on software and services. IBM's problem was that it had stopped listening to customers, Gerstner believed. The company should return to its original core competence of assembling information-processing systems for clients. Significantly, this

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[109] Bresnahan and Greenstein (1999).

[110] Gerstner (2002).

would mean abandoning the obsession with proprietary systems in favor of open platforms, of which, perhaps ironically, IBM would become a major proponent.

Smart clients no longer needed to be connected to servers in order to access basic computing functions. But it still made sense to connect clients together to communicate with one another and to share files and peripheral resources, in the context of individuals offices and, eventually, beyond. Indeed, an open modular system to interconnect virtually all servers and clients in the world – the Internet – would be the breakthrough technological advance of the late twentieth century.

The Internet is everyone's favorite example of successful industrial policy. In fact, however, although key pieces of the system most certainly grew out of federally funded projects, the development of the Internet was in important ways the antithesis of state planning. It was the product of radically decentralized and lightly governed collective invention among a large number of private and state actors, none of whom planned or foresaw the outcome of their joint activities.

The launch of the Soviet *Sputnik* satellite in 1957 touched off a boom in government-funded research and development. Unwilling to empower the military establishment he so well understood, Dwight Eisenhower moved to place control of the proposed funding bounty in the hands of scientists; and in 1958 Congress agreed to channel a $520 million appropriation to a newly created Advanced Research Projects Agency in the Pentagon.[111] Very quickly, however, the service branches reasserted control, and most

[111] Abbate (1999); Hafner and Lyon (1996). Over the years the agency, which I have previously referred to as DARPA, would oscillate between the acronyms ARPA and DARPA. At its founding and again now it is ARPA.

of the money was redirected to them and to NACA, now reconstituted as NASA. ARPA was left with a much-smaller though still-substantial budget of some $150 million – and no mission. Like its civilian counterpart the NSF, the agency turned to funding basic research, mostly at universities. One branch of research would be academic computer science, administered out of ARPA's Information Processing Techniques Office, whose first head, the psychologist J. C. R. Licklider, dreamed of a "symbiosis" between humans and computers. In 1966, Licklider's successor Robert Taylor initiated, out of personal interest, a project to link together the various incompatible computers ARPA was funding. This would be the Arpanet.

The Arpanet was to rely on the technique of packet switching, which had been invented independently in Britain and at the RAND Corporation (where, in the latter case, it had been seen as a way to make computer communications more resilient to a nuclear attack). Instead of routing each conversation over a single switched line as AT&T did, packet switching breaks messages up into small pieces, sending the segments out potentially at different times along different paths to be ultimately reassembled into a coherent message at the destination. (AT&T repeatedly told researchers this would never work, and the company refused to get involved except to lease dedicated wires.) To build the network, ARPA contracted with the Cambridge-based consulting firm Bolt, Beranek & Newman (one of whose principals was the same Leo Beranek who had helped design the Hush-A-Phone in the 1940s). Because the computers to be connected were built by different companies and used entirely different software systems, BBN had to employ what we would now call routers at each node. These "interface message processors" (IMPs) were refrigerator-sized Honeywell DDP-516 computers encased in military-grade steel cabinets. In September 1969, the first IMP was installed at UCLA, and a month later a second was set up at SRI in Menlo Park near Stanford. By the end of the year there were nodes at UC Santa Barbara and the University of Utah. More nodes followed. In 1972, ARPA was able to stage a spectacular demonstration of the network in a ballroom of the Hilton in Washington.

By that point, the Arpanet was not the only network ARPA was funding, and networking was proceeding in Europe as well. The problem was becoming not just how to connect computers together but how to connect entire networks together. In 1973, ARPA researcher Robert Kahn met with Vint Cerf, a Stanford computer scientist who had worked on the first IMP as a graduate student at UCLA. Within a year the pair had designed a set of protocols that would allow networks to talk to each other. Their TCP/IP protocols represented a highly modular open architecture that applied the principles of what Cerf and Kahn called end-to-end computing: all the intelligence should reside in the nodes and essentially none of it in the network itself. Overseen by an informal international working group of computer scientists, the TCP/IP protocols made it possible to connect together networks of virtually any kind. The resulting network of networks would become the Internet.

It is important to keep in mind that, at this point, the Internet was a tiny system limited to computer scientists with access to mainframe computers. It was also unused. Everyone recognized that the network was an important advance in computer science. But no one was quite sure what it was for. In 1972, a BBN programmer called Ray Tomlinson created a program to transmit messages between two separate computers at his company. Messaging on a single timesharing system was already common, but now it seemed possible to send messages over a network. Tomlinson even invented the ubiquitous @-sign to distinguish the recipient from the destination. As email software improved over the decade, email became the killer app of the Internet, albeit still limited to the elite with access to computers. The growth of email came as a shock to ARPA, which in 1967 had declared the ability to send messages between users "not an important motivation for a network of scientific computers."[112] By 1977 the agency had to admit that email had been "unplanned, unanticipated, and mostly unsupported." Email was one of innumerable inventions and improvements in the Arpanet that came from the decentralized activities of users.

By the 1980s, universities not connected to the Arpanet wanted access, as did researchers in fields other than computer science. The NSF started funding some of these connections, which the TCP/IP protocols facilitated. In 1983, the military spun off its own (classified and non-classified) sites, leaving the Arpanet wholly civilian though not yet commercial. Whereas in 1985 only about 2,000 computers had access to what was becoming the Internet, by 1987 that number had reached almost 30,000; and by October 1989 the figure had ballooned to 159,000.[113] Most of this growth was from new networks attaching to the Arpanet. The expansion coincided with the rise of the personal computer, as many of the added networks were in fact networks of workstations and PCs, typically connected together in office settings by local-area networks like the Ethernet system invented by Robert Metcalfe at Xerox PARC.[114]

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[112] Abate (1999, pp. 108-109).

[113] Abate (1999, p. 186).

[114] Hiltzik (1999, pp. 184-193).

At the same time, the NSF was putting together a network to hook together the supercomputer sites it was funding around the country. A central high-speed network connecting the supercomputers – the "backbone" – would connect in turn to a variety of regional computer networks. All would use the TCP/IP protocols. Before long, nodes on the aging Arpanet, some of them still powered by their original IMPs, began moving to the new NSF network. As the network billowed out, its participants began chafing at the restrictions of a government-owned network that barred all commercial use. In 1990, Stephen Wolff, who headed NSF's network operations, broached to users the possibility of privatizing the network. He found a broad consensus in favor. The transition would be made easy by the widespread availability in the private economy of advanced networking capabilities that had developed to serve businesses.

Indeed, some economic historians have even wondered, given the wealth of networking technology that attended the birth of the personal computer, whether something like the Internet might have emerged fairly quickly even had the Arpanet never existed.[115] Already by the mid-1980s, researchers at Stanford and elsewhere had developed multi-protocol routers that could handle TCP/IP as well as proprietary intra-office standards. The firm founded by some of the Stanford group, Cisco Systems, would provide much of the hardware and software for the commercial Internet, becoming the highest-valued firm in the world in 1999.[116] In the end, the principal contribution of the Arpanet was arguably not new technology that would never have been created privately but rather the early setting

115 Fishback (2007, pp. 519-520).

116 Greenstein (2015, pp. 167-168).

in place of open modular standards that created the path along which networking would travel.

In 1992, Congress passed legislation modifying the NSF charter to allow some commercial uses; and by 1995 the entire NSF backbone had been privatized.[117] One could imagine an early incarnation of the Internet having been handed off to a pre-deregulation AT&T. In other countries, postal-telephone monopolies would in fact gain control of computer networks. But by 1990, the Internet had grown beyond the management capabilities of any single firm, however large – this quite apart from AT&T's historic disdain for packet switching and the antipathy of the computer community to any kind of proprietary standards. Deregulation of AT&T was arguably important for the Internet in that it empowered long-lines competitors – the backbone would be supplied largely by the likes of MCI and Sprint – and effectively disempowered the FCC from imposing on the Internet the kind of regulation it had once imposed on telephony and broadcasting. The 1996 Telecommunications Act replaced the 1982 consent decree, essentially requiring the local phone companies to connect any services that asked to connect.[118]

The pre-commercial Internet had been governed by an Internet Advisory (later Architecture) Board composed of top computer scientists, notably including Cerf and Kahn. Below the IAB sat an Internet Engineering Task Force that saw to standards. This structure was preserved after commercialization, with the IAB rolled into a non-profit

[117] Greenstein (2015, pp. 84-86).

[118] Crandall (2005). At the same time, however, the Act contained pages of detailed requirements for how those interconnections were to be made and paid for, throwing telecommunications into unnecessary confusion for decades.

organization called the Internet Society. Thus the Internet would have some central direction, though more in the spirit of a gardener tending plants than like any kind of administrative coordination. In Shane Greenstein's phrase, it would retain governance at the edges.[119]

Ordinary PC users also craved connectivity.[120] Online services arose to fulfill this need. CompuServe had existed as early as 1969 but came into its own in 1980 when it was acquired by the tax-preparation firm H&R Block. In 1984, IBM and Sears came together to create Prodigy. America Online grew out of an online service called The Source, dating from 1979. Microsoft waded in with its MSN service. All of these required users to connect to a central server via telephone lines, using modems dialing into local phone numbers. Users typically paid a monthly fee plus a per-minute charge to access curated content, including magazine-like articles, online shopping (though as yet without the ability to enter credit-card details electronically), and, perhaps most notably, message boards and chat rooms in which members could communicate with like-minded fellow users.

These online services were all what we now call walled gardens. But the ability to communicate via email, including with those outside the garden, was a killer app here as well; and the online services began providing connection to the Internet as part of the package. Thanks to a marketing campaign of "carpet bombing" startup CDs to potential users, devised by the company's marketing head Jan Brandt, AOL became the largest of these services and a force in the personal-computer realm rivaling Microsoft. By the turn

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119 Greenstein (2015, p. 49).

120 McCullough (2018, pp. 52-68).

of the century, AOL was the most-popular access point to the Internet for PC users. As the Internet grew in capability, however, it became increasingly clear that the larger network itself would be able to provide all the functions of the walled gardens and more. The Internet would soon disintermediate the online services.

In the early 1990s, email over the Internet was easily accomplished within client programs and through the interfaces of the online services. (You've got mail.) But finding information and making connections on the Internet itself remained difficult even for adept users. Tim Berners-Lee, a British computer scientist at CERN, the European high-energy-physics laboratory in Switzerland, wanted to create tools to help his physicists locate information more easily on the Internet.[121] He and his colleagues put together a package of software that included a markup language called HTML – a simple programming language to format text – that would allow programmers to create applications with embedded clickable links that could take users directly to pieces of information on the network. Hypertext is an idea that some trace back to a 1945 article by Vannevar Bush.[122] It was certainly the dream of many computer visionaries, including the counterculture hacker Ted Nelson in 1974. To make hypertext a reality on the Internet, Berners-Lee needed a set of transmission protocols (HTTP) and a way to address information (universal resource locators – URLs). He also needed a rudimentary version of what came to be called a browser. Berners-Lee called his package of software the World Wide Web.

[121] Abbate (1999, pp. 214-216).

[122] Vannevar Bush, "As We May Think," *The Atlantic*, July 1945.

In 1991, CERN began distributing the software package over the Internet. Among its new users was a team at the National Center for Supercomputing Applications at the University of Illinois.[123] Like other NSF supercomputing sites, Illinois had received funding courtesy of the High Performance Computing Act of 1991, sponsored by then-Senator Al Gore. In fact, workstations and even personal computers, typically hooked in parallel, were already beginning to render the mainframe supercomputer obsolete. The Illinois group found itself awash in money but groping for a mission. By 1992, that mission had become networking; and an *ad hoc* team of students led by the undergraduate Marc Andreesen – in an archetypical hacker skunkworks – began to write code for what they believed would be an improved browser. They called it Mosaic. Within 18 months of its availability online, Mosaic had attracted some three million users, probably a plurality of the contemporary Internet, who were drawn to the new browser's ability (via an extension of HTML) to present images directly on web pages.

After he graduated from Illinois, Andreessen took a job in Silicon Valley. The Mosaic browser had impressed the entrepreneur Jim Clark, a co-founder of the workstation maker Silicon Graphics (famous for the computer-generated dinosaurs in *Jurassic Park*), who was looking to start a new company. Clark met with Andreessen in a Palo Alto coffee shop. Soon the pair founded what would ultimately be called Netscape.[124] They hired away most of the original Mosaic programmers from Illinois to design from scratch a new browser, ultimately to be called Netscape Navigator.

[123] Abbate (1999, pp. 216-218); McCullough (2018, pp. 7-17).

[124] McCullough (2018, pp. 17-37).

Navigator was fast, stable, feature rich, and optimized for contemporary 14.4 kbps modems; it was a generational advance over Mosaic. In October 1994, the company made a beta version available. In a mere two weeks, the beta grabbed 18 per cent of the browser market. In 1995, the beta and subsequent full version 1.0 captured 55 per cent of the market. By the end of 1996, 45 million copies had been downloaded, and Netscape held 85 per cent of the browser market. After only 18 months in business, and not yet making a profit, Netscape staged a now-storied initial public offering. In August 1995, the company put five million shares on sale for $28 a share. By the end of the day, the price had shot up to $71 a share.[125] Netscape instantly became a $2.7 billion company. The IPO caught the attention of Silicon Valley, the financial industry, and the general public, generating valuable free publicity not only for the company but for the Internet as well. Marc Andreesen would find himself on the cover of the February 19, 1996 issue of *Time*.

This is one of those rare cases in which some of the hype might be justified. The launch of Netscape Navigator represents a milestone in technological history much like the invention of the planar process in the 1960s, the development of the microprocessor in the 1970s, the introduction of the IBM PC in the 1980s, and the evolution of the physical Internet itself over that whole period. A fully functional browser suddenly provided a single simple platform with which users could harness vast knowledge resources and interact with millions of their fellows. In a world increasingly filled with personal computers, it dramatically reduced the transaction costs of exchange and unleashed – to use a term Bill Gates would soon popularize – a tidal wave of option value. The decade of

[125] Molly Baker, "Technology Investors Fall Head Over Heels for Their New Love," *The Wall Street Journal*, August 10, 1995.

the 1990s, especially the years after 1995, would be among the most remarkable of the century.

If there is a central theme to what the browser enabled, it is disintermediation – the increased ability of individuals to do for themselves what, because of costly information and geographic distance, had once required an intermediary. Many of the most extreme forms of this – like Uber and Airbnb – would not come online until well into the twenty-first century, when the PC itself would be eclipsed by more-compact devices. But it is worth remembering that most of the key forms of disintermediation took shape in the last five years of the twentieth century.

One obvious example is email. Two Apple employees called Sabeer Bhatia and Jack Smith realized that it should be possible to send and receive email right in the browser without having to go through an online service or use a machine-specific client program. They founded Hotmail in 1996.[126] (So obvious was this idea once revealed – an instance of what is called the paradox of information – that Bhatia and Smith found it necessary to use a fake business plan to vet VCs.) The most important function of the online services had been curation, the reduction of transaction costs by pre-organizing the user's information. Hackers and entrepreneurs quickly realized that a better way to reduce transaction costs, one that could access a far greater amount of information, might be to ask users what they were interested in and then find it for them. This would require what came to be called a search engine.[127] Jerry Yang and David Filo were Stanford graduate

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[126] Haigh (2008a, pp. 188-189).

[127] Haigh (2008b).

students who designed such an engine instead of writing their dissertations. They founded Yahoo! in 1996. A couple of years later, two other Stanford graduate students developed an even better search algorithm instead of writing their dissertations. Larry Page and Sergey Brin founded Google in 1998.

The most literal form of disintermediation came in the agora of buying and selling. A French-Iranian immigrant named Pierre Omidyar was intrigued with the idea of using the Internet to reduce the transaction costs of market exchange.[128] In 1995, he created the auction site that evolved into eBay. Repeated exchange with well-known trading partners reduces variety, but it limits cheating and misrepresentation. Anonymous trading of the sort eBay supplied drastically reduced the costs of search and negotiation between buyers and sellers, at the same time greatly expanding variety of choice; but it introduced costs of trust. Omidyar's associate Mary Lou Song realized the importance of creating trust within the Internet trading community, leading her to one of the signal inventions of disintermediation: the online rating system, which could substitute for, and even offer an improvement over, personal knowledge of one's trading partner. On the day eBay went public in September 1998, several months after hiring Meg Whitman as CEO, its stock price immediately doubled, creating a $2 billion company.

The business model of eBay was pure disintermediation – hooking up buyers and sellers but otherwise staying out of the way. Most of the online commerce that the Internet would facilitate sought not to eliminate intermediation completely but simply to reduce its footprint and to disconnect it from geography. The most famous example of this, of course,

[128] McCullough (2018, pp. 108-119).

is Amazon, founded by Jeff Bezos and his then-wife MacKenzie in 1994.[129] Also attuned to the costs as well as the benefits of anonymous online trading, Bezos famously chose to begin as a bookseller because books are a prototypical undifferentiated commodity. Putting a bookstore online opened access to many more customers; but it also allowed the bookstore to provide a far wider variety of titles than any bricks-and-mortar store. By one estimate, at the turn of the century Amazon stocked 23 times more books than the average large chain bookstore and 57 times more than a typical independent bookstore.[130] In the year 2000, that translated into a gain in consumer welfare from variety alone of as much as $1 billion, which was seven to ten times greater than the gain from the lower prices Amazon charged.

Soon, of course, Amazon moved beyond selling only books, becoming the "everything store" Bezos had imagined. This is not a new model. It is in fact a much-sped-up version of the mail-order business model of Sears Roebuck and Montgomery Ward early in the century. Just as Sears once had, Amazon created high-throughput fulfillment centers; and just as Sears had depended on the railroads, Amazon could take advantage of the now-deregulated delivery industry. Netscape had already created a crucial prerequisite for seamless online trading: the Secure Sockets Layer technology, which for the first time made it safe for users to input their credit-card details directly online. In the twenty-first century, Amazon would also move into the arena of pure disintermediation, setting up the

129 McCullough (2018, pp. 94-107).

130 Brynjolfsson, Hu, and Smith (2003).

Amazon Marketplace, which allows thousands of mostly small sellers to market their wares through Amazon's platform.

And as the personal computer enabled the Internet, so the Internet disintermediated the personal computer. While still an undergraduate at the University of Texas in 1983, Michael Dell began selling customized computers using parts available from catalogs.[131] In 1984, he founded Dell Computer. Bolstered by contracts with the state government, the company was able to parlay its mail-order-plus-customization strategy into prominence among PC makers, competing with conventional firms like Compaq and Hewlett-Packard and with other mail-order houses like Gateway 2000. But by the early 1990s, Dell was stumbling, especially after it attempted to sell through retailers and other third-party channels. All of that changed with the coming of the Internet. Returning to its direct-to-customer roots, Dell became the first and most successful Internet retailer of personal computers. In 1996, when Amazon was selling $15 million worth of books a quarter, Dell was selling $90 million worth of PCs a quarter.[132] In 2002, the company was the largest Internet vendor in the world, with 22 per cent of all online retail sales by value.

In effect, Dell figured out how to use the Internet to accomplish what IBM had failed to do: make a success of the personal computer without controlling any of the bottlenecks in the PC architecture. Dell did this not by attempting a proprietary strategy but precisely by understanding and embracing the open modular character of the PC.[133] By acquiring standard parts in the market, the firm could be assured of having the best,

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131 Fields (2004, pp. 178-219).

132 Fields (2004, p. 187).

133 Baldwin and Clark (2006).

cheapest, and newest components. And by assembling the PCs on demand, it could virtually eliminate inventories of parts and of finished machines. In 2002, the year Dell surpassed Compaq as the largest maker of PCs, Dell was carrying four days of inventory to Compaq's six weeks.[134] The actual assembly of a PC is a small fraction of the cost of the device; so, in this respect, even though Dell is a manufacturer and Amazon just a reseller, the two operations are fundamentally similar, both based largely around logistics. Indeed, Dell soon stopped literally buying components in the market – for, as Coase pointed out, constantly finding trading partners and negotiating prices is costly – and began integrating its computerized purchasing system with the systems of key suppliers. In effect, Dell began operating a just-in-time inventory system not unlike those of car manufacturers like Chrysler, even if Dell's ease of assembly and just-in-time relationship with customers was something the auto industry could only dream about.[135] Michael Dell called this "virtual integration."

In the late 1990s, computers and information technology played a crucial role well beyond strictly online commerce. Indeed, even the retailer with the largest bricks-and-mortar footprint was driven by a computer-based logistics system not unlike that of Amazon and Dell. In the early twenty-first century, Wal-Mart had something like 4,000 big-box stores in the U. S. (counting Sam's Club), handling nearly 10 per cent of non-automobile retail sales.[136] In its way, Wal-Mart also represented a method of reducing consumer transaction costs: because each store carries a wide (but not necessarily deep)

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[134] Fields (2004, p. 166).

[135] Fine (1998).

[136] Basker (2007).

assortment of goods, customers could expect to find what they need in one trip to a single location. Wal-Mart's business model was also not new: it was right out of the early-century playbook of the Great Atlantic & Pacific Tea Company. In its quest to lower costs, however, Wal-Mart had an advantage over the A&P. Computers first appeared in the company's inaugural distribution center as early as 1969. By the 1970s, all Wal-Mart stores were networked with headquarters. Bar-code readers appeared in the 1980s. And in 1990 Wal-Mart began integrating its suppliers into its computerized inventory system.

It was in this period that Wal-Mart began selling groceries, at prices 15 to 25 per cent lower than those at traditional grocery stores. The entry of supercenters into competition with traditional food markets in the period 1998-2003 lowered average food expenditure by 25 per cent, amounting to an average of almost $800 annual savings per household.[137] The effect was greatest for those at the bottom of the income scale, where the appearance of a Wal-Mart nearby meant an effective increase in income of 6.5 per cent for those in the bottom income quintile. Effects were almost certainly just as large for non-food items, a total benefit to the poor rivaling in size federal programs like food stamps and the Earned Income Tax Credit.

On the whole, the second half of the 1990s was a remarkable period of prosperity and growth in the U. S.[138] Real GDP per capita grew at an average annual rate of four per cent over the 1995-2000 period, a rate not seen since before 1973. Whereas the unemployment rate had been 7.8 per cent in 1992, it had fallen to 4.1 per cent by the end

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137 Hausman and Leibtag (2007).

138 Blinder and Yellen (2001).

of the decade, the lowest level since the 1960s. There were doubtless many reasons for this prosperity. The Fed was pursuing an easy-money policy, with the real federal-funds rate at zero. The Clinton administration and Congress had made a credible commitment to reducing the budget deficit. But real forces were probably more important. The U. S. private sector was beginning to see the benefits of the creative destruction of the 1970s and 1980s. Inefficient plants, firms, and industries had shut down, replaced by leaner and more efficient ones. Most significantly, the new information-technology industries were finally beginning to have an impact.

In 1987, Robert Solow had famously quipped: "You can see the computer age everywhere but in the productivity statistics."[139] By 1995, you *could* finally see the computer age in the productivity statistics. Econometric evidence shows a structural break in 1995, when both labor productivity and total-factor productivity increased significantly over what they had been in the 1973-1995 period, albeit not quite to the levels of the 1947-1973 period.[140] This productivity increase was based broadly throughout the economy. Sectors producing information-technology products generated large productivity gains, but so did other sectors that invested heavily in the use of IT in the early 1990s. At the beginning of the twentieth century, the innovation of electricity did not yield a significant productivity gain until complementary assets, notably the design of factories, had been slowly altered to take advantage of the new technology.[141] So too information technology began to affect aggregate productivity at the end of the century only after users "co-

[139] Robert Solow, "We'd Better Watch Out," *The New York Times Book Review*, July 12, 1987, p. 36.

[140] Stiroh (2002).

[141] David (1990).

invented" new organizational forms and behavior patterns complementary to cheap computers and widespread networks.[142]

In 1995, Bill Gates believed he saw the computer age – of the future. What he envisioned was an information superhighway of interactive multimedia communications. "The Internet is not the information highway I imagine," he wrote in his book published that year, "although you can think of it as the beginning of the highway."[143] The Internet was to his imagined highway as the Oregon Trail of the nineteenth century was to Interstate 84. By the end of 1995, however, Microsoft staff had persuaded him otherwise.[144] They sat him down in front of Netscape, and he spent most of the night surfing the web. Gates quickly produced an internal document called "The Internet Tidal Wave," dramatically redirecting the company toward the contemporary Internet. He now understood that the superhighway was already here. Microsoft had licensed technology from Mosaic, the browser Andreesen had left behind at Illinois, to include rudimentary Internet capabilities in the Windows 95 operating system. Gates now ordered a crash project to create a full-fledged web browser, Internet Explorer.

Netscape's pricing model was "free, but not free."[145] The browser could be downloaded and used for free by students and educational institutions and by everyone during a 90-day trial period. After the trial period, people were expected to buy a license, though there was no enforcement mechanism. In the end, many users did pay, especially

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142 Bresnahan and Greenstein (1996).

143 Gates (1995, p. 95).

144 Cusumano and Yoffie (1998, pp. 108-111); McCullough (2018, pp. 38-51).

145 Cusumano and Yoffie (1998, pp. 98-99).

businesses that expected technical support; and the company also charged PC manufacturers who wanted to pre-load the software on their machines. Thus Netscape made money off the browser, even though its real business model had always been to make money from the complementary server software it was developing.

Microsoft announced that the new Internet Explorer would be completely free for everyone. The software would also ship with Windows 95, into which it was integrated along some dimensions. In addition, the company began pressuring its trading partners to adopt IE, sometimes with bribes, sometimes with threats.[146] In 1997, KMPG switched all its employees from Netscape to IE when Microsoft made the consulting firm a deal too good to resist. Apple made IE its default browser on the Mac after Microsoft invested $150 million in Apple and agreed to provide word processing and spreadsheet software. Compaq, Microsoft's largest customer, agreed to preload only IE after Microsoft threatened to revoke Compaq's operating-system licenses. Perhaps most significantly, AOL made IE its default browser in exchange for a placement of the AOL icon on all Windows startup screens. (In giving such placement to AOL, Microsoft effectively sacrificed its own entry into the online-service market, MSN. The company considered the trade well worth it.) Even though Netscape quickly made its browser completely free, its share of the market plummeted as IE's share ascended.

Why was Microsoft so anxious to obliterate Netscape? Gates understood clearly that a fully functioning browser was, at least potentially, a threat to the Windows operating system, the company's cash cow. As we now know, it would become possible to run more

[146] Cusumano and Yoffie (1998, p. 146).

and more applications directly in the browser, making irrelevant which operating system was running underneath the browser. (Hotmail is an early example of this. Microsoft bought Hotmail in 1997.) For his part, Marc Andreesen felt exactly the same way. Netscape, he vowed, would reduce Windows to a minor set of "slightly buggy device drivers."[147]

The government began looking askance at Microsoft as early as 1990, when the FTC and then the Department of Justice started investigating the firm's contracting practices.[148] In 1995, Microsoft signed a consent decree agreeing not to bundle software with the operating system unless, significantly, the software was "integrated" into the operating system. At Netscape's urging, the DOJ began another investigation in 1996, and in 1997 accused Microsoft of having violated the consent decree. A district court issued a preliminary injunction against bundling IE with Windows 95. An appeals court would eventually overrule the district court on the grounds that IE qualified as integrated with the operating system. But in May 1998, even before the appeal had been decided, the DOJ, under Assistant Attorney General Joel Klein, filed suit against Microsoft under Sections 1 and 2 of the Sherman Act.[149] The twentieth century would end with another dramatic

147 Cusumano and Yoffie (1998, p. 40).

148 Lopatka and Page (1999, pp. 172-176). During this period, the government also challenged, and ultimately prevented, Microsoft's acquisition of Intuit, the maker of personal-finance software; and it initially questioned the bundling of MSN with Windows, though MSN's lack of success made that issue moot.

149 *United States v. Microsoft Corporation*, Civil Action No. 98-1232 (Antitrust), complaint filed May 18, 1998. Available at https://www.justice.gov/atr/complaint-us-v-microsoft-corp, accessed June 26, 2021. The suit was joined by the governments of 20 states and the District of Columbia. I will refer to the plaintiffs as "the government."

antitrust case, this one aimed at the company that many saw as the successor to IBM in the American computer industry.

At first glance, this might look like a case of tying. As we have seen, the Chicago School argued that a firm with market power in one product cannot leverage that market power into a second market by tying two goods together. There is only one "lump" of market power. And it certainly makes no sense to think that, by tying punched cards to the sale of tabulating machines, IBM was trying to take over the business of printing small pieces of cardboard. But in tying IE to Windows, might Microsoft not have been using its market power in the operating-system market to help shape in its favor the evolution of a promising new technology? When the government made a leveraging claim of this sort at the beginning of the trial, Microsoft called for summary judgment to dismiss the charge; and the trial judge, Thomas Penfield Jackson, immediately granted the motion, explicitly invoking the Chicago School view: the "Third and Ninth Circuits and many commentators have rejected the [monopoly leveraging] theory outright, as contrary to both economic theory and the Sherman Act's plain language."[150] The case would be tried on other grounds.

Central to the government's theory of the case was the idea of an "applications barrier to entry."[151] We saw that, in controlling the operating system, Microsoft controlled one of the bottlenecks of the PC architecture. Why was this a bottleneck? The answer lies in perhaps the most salient economic idea of the era: *network effects*.[152] Bill Gates invoked

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150 Evans (2002, p. 7).

151 Melamed and Rubinfeld (2007, pp. 291-292).

152 For a much more careful discussion of these issues in the antitrust context, see Langlois (2001).

this idea himself when he wrote that he had wanted MS-DOS to benefit from the same kind of forces that had propelled the VHS standard to prominence over the Betamax. As MS-DOS (and then Windows) became the most popular operating system, it attracted an increasing number of compatible software applications; and the increasing number of software applications in turn made the Microsoft operating system more desirable for users. Because the costs are high of converting an application from one operating system to another, anyone offering a competing operating system, even a system perhaps superior along some dimension when considered in isolation, would have the daunting challenge of overcoming its relative dearth of applications. Note that, like all real barriers to entry, the applications barrier is the end traceable to a property right: Microsoft owned the copyright on the operating system's source code (a *de jure* property right) and the company also refrained from making the source code publicly available (a *de facto* property right).

Because it possessed this barrier to entry, Microsoft could of course earn rents.[153] But by the standard that Learned Hand articulated (but did not apply) in *Alcoa*, a firm could achieve such a position legally through superior skill, foresight, and industry (or even luck). The government had to prove that Microsoft was actively maintaining its position through anticompetitive practices – that it was engaging in monopolization as understood under section 2 of Sherman. In expending resources to create a browser only to give it away, in bribing trading partners to adopt IE, in destroying good will by threatening other trading

[153] The meaning of a "competitive price" in software is far from clear. Because software is a high-fixed cost industry, marginal-cost pricing would not cover the fixed costs of software development. A firm that did not price at least at average cost would not stay in business long, all other things equal. By one calculation, Microsoft charged far less for Windows than a profit-making monopolist should have in theory, suggesting that the firm did not consider the applications barrier to offer all that much protection (Reddy, Evans and Nichols 2002).

partners, and in sacrificing the MSN online service, the government argued, Microsoft was burning some of its rents in an effort to exclude Netscape from the browser market. Microsoft would not be accused of tying; it would be accused of predatory behavior akin to predatory pricing.[154]

The parties approached the case with two very different strategies.[155] The government stuck to a focused script. It narrowly defined the relevant market as that for operating systems for Intel-compatible personal computers. Because Microsoft held some 95 per cent of that market, it was a monopoly. The government then pressed its case that Microsoft's contracting practices constituted anticompetitive exclusion that maintained its monopoly and thus violated Section 2. By contrast, Microsoft waged what could only be called a Schumpeterian defense. The company denied all charges, and it portrayed its position as that of a dynamic competitor in an ever-changing market, perennially besieged by threats ranging from the dimly perceptible to the radically unknown. "In the future," one Microsoft executive was paraphrased as testifying, "users may simply plug their computers into cable outlets and get whatever programs cable providers offer. Small, handheld computing devices could wipe out the PC, just as the PC wiped out the

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154 The analogy is far from perfect and may be misleading. If a firm tries to drive a rival out of business by lowering its price below cost, that lower price benefits consumers in the short run (and often in the long run as well if, as is often the case, the would-be predator cannot keep new competitors from coming back into the market once it raises the price back up). In this case, the government argued, Microsoft's behavior harmed Netscape without conferring any benefits on consumers. Notice also that, in a normal predatory-pricing case, the would-be predator is trying to keep a rival out of the predator's own existing market. In this case, Microsoft was accused of keeping Netscape out of a new and developing market. Yet in charging Microsoft with monopoly, the government examined only Microsoft's share of the existing operating-system market and did not consider browsers and other potential non-operating-system competitors as part of the relevant market.

155 Melamed and Rubinfeld (2007). For a description of the arguments of the government's testifying economists, see Bresnahan (2002); and for those of Microsoft's economists, see Evans, Nichols, and Schmalensee (2001).

mainframe."[156] A graphical exhibit depicted these threats, many of them in the form of question marks, impinging as arrows upon the company. This elicited titters from the courtroom, and the argument was widely mocked in the press.

On April 3, 2000, Judge Jackson ruled for the government on almost all counts. He also accepted the government's proposed remedies. These included not only conduct remedies – specifications of the behavior Microsoft could no longer engage in – but also a structural remedy: the company was to be broken in two parts, one retaining ownership of the operating system and one having ownership Microsoft's successful productivity-software business (and IE). In February 2001, the appeals court for the District of Columbia met *en banc* to review the case. The court upheld some of the district court's findings and reversed others.[157] But the appellate court was especially miffed that Jackson had ordered a breakup of Microsoft – a remedy seemingly disproportionate to the government's claims – without a remedy hearing; and the judges remanded the case back to the district court.[158] (Indeed, it is unclear how that remedy would have corrected the issue at the base of the government complaint. A descendent of Microsoft would still have controlled the operating-system bottleneck.)

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156 William Saletan, "Microsoft Plays Dead," *Slate*, January 28, 1999.

157 *United States of America, Appellee v. Microsoft Corporation, Appellant*, 253 F.3d 34 (D.C. Cir. 2001). Importantly, the appeals court left standing the finding that Microsoft had a monopoly int eh market for Intel-compatible personal computers – on the grounds that Microsoft had never offered rebuttals to the government's claims. This opened the door to a welter of private antitrust suits against Microsoft. (Disclaimer: I was a testifying expert for the plaintiff in one of these private cases, *Bristol Technology, Inc. v. Microsoft Corp*., 127 F. Supp. 2d 85 (D. Conn. 2000).) Opening a playbook it would use repeatedly in the twenty-first century, the European Union also sued when a European firm that made audio-player software complained that Microsoft had included an audio player in Windows.

158 The appeals court also removed Jackson from the case because he had "engaged in impermissible *ex parte* contacts by holding secret interviews with members of the media and made numerous offensive comments about Microsoft officials in public statements outside of the courtroom, giving rise to an appearance of partiality."

Ultimately, the DOJ (by then under the George W. Bush administration) and the states agreed to a settlement with Microsoft on a set of detailed conduct remedies – but no breakup. This was essentially a regulatory solution: Microsoft's conduct would be overseen by a three-member panel of computer experts for five years.[159] Overall, the case took more than three years from filing to settlement, short by the scale of cases like *IBM* but glacial by the standards of what management writers had begun to call "Internet time." And, although Microsoft and all future firms would be warned away from certain kinds of contracting practices – perhaps increasing the incentive to acquire complementary firms rather than contract with them – the case did nothing to change the market in any fundamental way. Already in 1999, AOL had acquired Netscape for $10.2 billion in stock.[160] Andreesen and many others quickly fled the company, which retained IE as its default browser. In the view of the distinguished antitrust scholar Herbert Hovenkamp, "the Microsoft case may prove to be one of the great debacles in the history of public antitrust enforcement, snatching defeat from the jaws of victory."[161] Writing in 2005, Hovenkamp envisioned an industry continuing along its same path, with Microsoft in control of a world dominated by the personal computer. Maybe another antitrust suit would soon be necessary.

That is not what happened. In the twenty-first century, everything Bill Gates feared would come to pass.

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159 https://www.justice.gov/atr/case-document/stipulation-65. Accessed June 27, 2021.

160 "AOL Says Deal to Acquire Netscape Has Been Completed," *The Wall Street Journal*, March 18, 1999. AOL was interested in Netscape's server-software business, not in the browser.

161 Hovenkamp (2005, p. 298).

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