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When is a Microprocessor not a Microprocessor? The Industrial Construction of Semiconductor Innovation[1]

In the early 1990s an integrated circuit first made in 1969 and thus antedating by two years the chip typically seen as the first microprocessor (Intel's 4004), became a microprocessor for the first time. The stimulus for this piece of industrial alchemy was a patent fight. A microprocessor patent had been issued to Texas Instruments, and companies faced with patent infringement lawsuits were looking for prior art with which to challenge it.[2] This old integrated circuit, but new microprocessor, was the AL1, designed by Lee Boysel and used in computers built by his start-up, Four-Phase Systems, established in 1968. In its 1990s reincarnation a demonstration system was built showing that the AL1 could have operated according to the classic microprocessor model, with ROM (Read Only Memory), RAM (Random Access Memory), and I/O (Input/Output) forming a basic computer. The operative words here are could have, for it was never used in that configuration during its normal lifetime. Instead it was used as one-third of a 24-bit CPU (Central Processing Unit) for a series of computers built by Four-Phase.[3]

Examining the AL1 through the lenses of the history of technology and business history puts Intel's microprocessor work into a different perspective. The differences between Four-Phase's and Intel's work were industrially constructed; they owed much to the different industries each saw itself in.[4] While putting a substantial part of a central processing unit on a chip was not a discrete invention for Four-Phase or the computer industry, it was in the semiconductor industry. Although the AL1 was in many ways technically superior to Intel's first generation microprocessors, its location in the computer industry led to a different, and ultimately truncated development trajectory. Flexibility was the hallmark of Intel's microprocessor, with Intel and its customers finding countless applications for it, while the industrially constructed rigidity of the AL1 limited its applications.

The story of the AL1 and Four-Phase Systems provides a case study of a start-up in Silicon Valley's adolescent period. Four-Phase owed its origins to a visionary engineer working for an inattentive wealthy company willing to fund work in a new area, but unable (or unwilling) to manage it so that it would benefit the company. Four-Phase is also important as a representative of the successful Silicon Valley firms that do not achieve the level of public visibility of an Intel or Apple. Looking at both Four-Phase and Intel provides a sense of the diversity of Silicon

Figure 1. Lee Boysel (right) with Cloyd Marvin, another former Fairchild engineer who moved to Four-Phase Systems, looking at the layout of Four-Phase's AL1 integrated circuit. Courtesy Lee Boysel.

Valley start-ups during this period, a diversity that increased the chance that some would succeed.[5]

Lee Boysel, MOS Maverick

The essential background to both the AL1 and Intel's 4004 is the MOS (Metal-Oxide-Semiconductor) technology and the MOS work done at Fairchild Semiconductor in the 1960s. The MOS transistor came onto the agenda of the semiconductor industry in the early 1960s, primarily because it was simpler to build than the dominant bipolar transistor, allowing one to put many more transistors on a chip. However its drawbacks included a dependence on the characteristics of the surface of the silicon, which could not be well controlled, and a much slower speed than the bipolar transistor. Advocates of MOS technology searched for an application which would take advantage of its characteristics.[6]

Fairchild Semiconductor, the semiconductor industry's most dynamic firm in the 1960s, supported two different and competing MOS programs. The primary one was at Fairchild's research and development laboratory in Palo Alto, California under the direction of Gordon Moore. A major part of the R&D program was devoted to understanding the chemistry and physics of MOS structures and developing methods of fabricating them. The group was by and large made up of chemists, physicists, chemical engineers, and electrical engineers concerned with the physical and chemical processes involved in making semiconductors. (They had almost no background in computing.) The nucleus of this effort left to form Intel.[7] The other group, almost a bootleg operation, was in applications, a few miles down the road in Mountain View, but a world away in its approach to the technology. This group consisted of electrical engineers who were interested in using MOS technology to design complex systems on a single chip. While they were not strong in semiconductor processing, they understood computers and circuits. They were led by Lee Boysel, a highly creative and maverick MOS devotee.[8]

Lee Boysel's MOS work started with an epiphany two years before he joined Fairchild. In 1964 he was an electrical engineer and electronics enthusiast just out of the University of Michigan, working at Douglas Aircraft in Santa Monica, California. At that time Frank Wanlass, one of the first proponents of MOS technology, visited and showed him that a twenty-bit shift register could be built on a single MOS chip, something that would have taken many circuit boards using individual transistors.[9] Boysel became a believer in the possibilities of MOS technology and from that point worked on it exclusively. He designed MOS circuits at Douglas and then moved to IBM in Huntsville, Alabama, where he designed MOS circuits for use in space applications.[10]

Boysel was highly individualistic, unwilling to sacrifice his own personal goals for the good of the larger organization. The key characteristics of his working style were a preference for hands-on work over analysis, a willingness to work extremely long hours, and an impatience that led him to circumvent formal bureaucratic channels. He had a home laboratory equipped with government surplus equipment he had bought while he was at Douglas. On the evenings and weekends, he would frequently carry his circuit design projects back to his home lab. While this might suggest someone who was doing the company's work on his own time, in reality the opposite was much more nearly true. At both Douglas and IBM he had carried his MOS efforts far beyond his mandate or the companies' interests; this pattern would continue when he joined Fairchild Semiconductor in 1966.

Boysel's experience at Fairchild shows how a person in a marginal position at a large corporation could use that position to accomplish his goals even when they were not congruent with the corporation's. At the time he joined Fairchild, he benefitted from the uncertainty surrounding the unproven MOS technology. No one knew which, if any, applications would be successful. MOS technology at the time was a minuscule portion of Fairchild's business, and managers concerned themselves more with the dominant bipolar technology. Boysel was in a marginal position at Fairchild and took full advantage of it. While Fairchild managers might have a justifiable tentativeness in their approach to the new technology, Boysel knew exactly what he wanted to do and charged ahead. He designed a 256-bit ROM before his management knew anything

Figure 2. Photograph of eight-bit arithmetic unit integrated circuit designed by Lee Boysel at Fairchild circa 1967. This photograph comes from a Fairchild publicity booklet of the late 1970s or early 1980s containing pictures of some of the most important integrated circuits Fairchild had designed. The integrated circuit was called 'the first standard MOS product for data processing applications.' No mention was made of its lack of success in the market or of Boysel's role in designing the part. The size of the chip is 110 × 80 mils. Source: Fairchild Camera and Instrument, A Solid State of Progress (n.p.: Fairchild Camera and Instrument, n.d.).

about it. He followed this with an eight-bit adder in MOS. Neither part was commercially successful.[11]

In 1967 Boysel wrote a manifesto putting his work into perspective and revealing his plans. In a single sheet of paper consisting of a computer block diagram and a third of a page of text, Boysel showed that an entire computer (including memory) could be made out of MOS technology. At this time no computer in production had been built using semiconductor memory, MOS or bipolar. Proposing a computer built entirely from bipolar technology would have exhibited forward thinking; using MOS technology was radical.[12]

The bulk of the computer would be made from six different MOS part numbers. He described the CPU element as a '4 bit wide slice with all op code decoding and branch instruction built-in.' The ROM chip (at IBM he had studied the System/360 architecture and gotten the idea of microprogramming using ROM) would contain either four to eight thousand bits, while the RAM chip would contain either 512 or 1024 bits. Perhaps Boysel's most extraordinary claim was that one could build a bona fide computer out of MOS technology. At the time most people thought MOS technology was best suited for calculators; Boysel claimed that with proper design, it could be used to build mainframe computers.[13]

Although the manifesto included a business analysis, purporting to show why it made sense for Fairchild, Boysel's vision was a personal one, not closely tied into considerations of Fairchild strategy. Boysel's vision was one that ultimately would not be satisfying to either Fairchild or its customers. Were customers to adopt Boysel's approach, it would take away dramatically from Fairchild's existing bipolar business and require a radical reorganization of the company. In any case, customers had ample reason to be hostile to Boysel's plans. The use of small scale integration (that is a few logic circuits on a chip) allowed computer makers to design and implement a computer in the way they believed optimal. Boysel was proposing to reparse the task so that his group encroached on the responsibilities of computer system designers. The jurisdictional question was compounded by the fact that Boysel's plan threatened to take away one of the computer makers' main sources of added value, their design of the computer. In any case Boysel did not have Fairchild's interests in mind: he was intending to start his own computer company and his manifesto described the approach he would use. Fairchild was unwittingly providing the early development funding for this start-up.[14]

Although none of Boysel's designs was a business success, Fairchild, flush with money and not fully aware of his motives, authorized him to hire others to form a MOS design group. Fairchild management appears to have valued Boysel because he gave the company a credible presence in MOS. (While the long-term outlook for MOS was uncertain, a few start-ups had gathered a lot of attention in the trade press for their work on MOS.) Boysel and his group designed enough MOS parts to fill a catalog, although none of them were sold in any volumes. He wrote several articles in the trade press describing his MOS parts, even though he had designed them not with Fairchild's need in mind, but the requirements of his own computer.[15]

Given the marginal status of MOS technology at Fairchild, and Boysel's view of himself as an insurgent, he was successfully able to create an environment where those he hired saw their primary allegiance to him, rather than to Fairchild Semiconductor. By mid-1968, Boysel and his group had designed the key parts necessary to build a computer from MOS technology. With his initial development work done, he left to start his own company in October 1968.[16]

Boysel's company started as a partnership, with two other engineers from his group at Fairchild joined by several outsiders. They worked in a rented dentist's office, using equipment Boysel had in his home laboratory. No one was paid while Boysel sought long term funding. Four-Phase Systems was incorporated in February 1969, based on $2 million of long-term notes. A large portion of the funding came from Corning Glass Works, which also owned Signetics, a major semiconductor manufacturer. At this point, other members of his Fairchild group joined him. The name Four-Phase hinted at Boysel's technological enthusiasm, for it was an abstruse type of MOS circuitry.[17]

Boysel planned to build the computer he had described in his September 1967 MOS design manifesto. The computer would use MOS technology throughout. Through the use of four-phase circuitry, which made possible the use of very small MOS transistors, Boysel was able to build much denser chips than he had envisioned earlier. The computer would be equivalent in power to a medium-sized IBM System/360. Boysel and his company sought a niche for their system, finally settling on using it as a terminal controller, specifically a plug-compatible replacement for IBM systems. This provided Boysel access to an established market and lowered the risk for potential customers, for if his system proved unsatisfactory, they could quickly replace it with an IBM system.[18]

Since Four-Phase was built on Boysel's integrated circuit designs but a computer start-up could not justify the costs of a dedicated semiconductor fabrication facility, Boysel made arrangements to assure the company access to integrated circuit manufacturing capacity. At the time Boysel left, a Fairchild colleague who worked in MOS manufacturing also left to start Cartesian, a company which would process MOS wafers for Four-Phase and other companies who were able to design their own circuits. Cartesian implemented the MOS process that had been used at Fairchild manufacturing, and that Boysel and his group had used in all their previous designs. Without this continuity in the manufacturing process, Four-Phase would have had to substantially modify its circuit designs, extra work that would be costly in time and money for a start-up. The two firms formed a dyad, with Cartesian's creation essential to Four-Phase, and Boysel arranging financing for it along with his own company.[19]

By the spring of 1970, Four-Phase had an engineering-level system operating, and it publicly introduced its system that fall. By June of 1971, Four-Phase systems were in operation at Eastern Airlines, United Airlines, Bankers Trust, and McDonnell-Douglas. One user asserted the cost of the Four-Phase system was roughly half of an equivalent IBM system. All users interviewed in an article in *Computerworld* gave very positive reports on their experiences with the system. By March 1973, Four-Phase had shipped 347 systems, with 3,929 terminals to 131 different customers.[20]

The AL1

The heart of the system was the AL1 chip, which Boysel had conceived of and designed while still at Fairchild. The AL1 contained an eight-bit arithmetic unit and eight eight-bit registers (including the program counter). It was an extremely complex chip, with over a thousand logic gates in an area of 130 × 120 mils. (To give a point of comparison with later integrated circuits, this was roughly the same number of logic circuits in Intel's 8008 in an area the size of Intel's 4004.)

One should point out the obvious: there was no such thing as a microcomputer or a computer on a chip at this time. (At the time, the term microprocessor had a different definition, meaning a microprogrammed processor with RAM and ROM.) Having one's integrated circuit recognized as a computer on a chip depended not on meeting some fixed set of criteria, but on making a claim to the title and subsequently convincing the semiconductor and computing communities of the validity of that claim. Boysel and Four-Phase might have called the AL1 a computer on a chip and one can imagine a scenario where this claim would have later engendered some debate with Intel and others about what constituted a computer on a chip. Boysel made no claims for his chip and there was no such discussion. And in fact, Boysel and Four-Phase seem to have had a hard time coming up with a descriptive name for the AL1. In an April 1970 article in *Computer Design*, Boysel and one of his colleagues alternately called the AL1 'the main LSI block of a low-cost fourth-generation commercial computer system,' an 'eight-bit computer slice,' and an 'arithmetic logic block.'[21]

Although the AL1 was an outstanding piece of engineering work, essential to the success of his overall computer, Boysel did not see it as an innovation in and of itself. Boysel had done two previous designs of adders or arithmetic units at Fairchild and the AL1 represented simply a continuation of that work; it was a change in degree not a change in kind. The computer system that Four-Phase had developed had required the design and fabrication of a number of complex and innovative inte-

Figure 3. Photograph of AL1. As part of the AL1's 1990s reincarnation as a microprocessor, this photograph has overlays identifying the chip's different functional elements, a practice common in microprocessors. Notice that the AL1 has forty input/outputs, the pads on the perimeter of the chip. The size of the chip is 130 × 1210 mils. Courtesy Lee Boysel.

grated circuits. Among these, the AL1 was not uniquely important or innovative—each was needed to build the system.

To Boysel the AL1 was neither a computer on a chip nor a processor on a chip. First of all, because Four-Phase's computer was 24-bits wide, three AL1's were required per system. Furthermore in Four-Phases's nomenclature the Central Processing Unit (CPU) circuit board was made up of three AL1 chips, three chips called Random Logic (RL), and three ROMs. The CPU included the control store (ROM). The AL1 was not a microprocessor under the existing definition of that term.

In 1971 and 1972 respectively, Intel introduced the 4004 and 8008 integrated circuits which are now considered the first microprocessors. [22] By metaphorically putting the AL1 alongside them, we can get some idea of how Four-Phase's position in the computer industry shaped the AL1 and its development. Intel trumpeted the announcement of the 4004 as 'a new era of integrated electronics' and a 'microprogrammable computer on a chip,' for the obvious reason that the more this thing caught the users' eye, the more likely they were to buy it. (The 4004 was patently

Figure 4. Photograph of the 4004, Intel's original 4-bit microprocessor chip. Notice the 16 input/output pads around the periphery of the chip. The chip size is 170 × 125 mils. Courtesy Intel Corporation.

Figure 5. Photomicrograph of the 8008, Intel's 8-bit microprocessor chip. Notice the 18 input/out pads around the chip's periphery. The chip size is 170 × 125 mils. Courtesy Intel Corporation.

not a computer on a chip; even calling it a CPU on a chip represented a diminution of that term.) The AL1 received no such publicity. What mattered to Boysel, as an entrant into the computer business, were the characteristics of the overall system, such as performance or cost. Unless it offered some such system benefit a customer could readily understand, he had no reason to claim his AL1 represented something new. Boysel's nonchalant attitude toward putting a computer on a chip can be seen in his statements made for an article published in *Electronic Design* in February 1970. At this time what would become the 4004 and 8008 microprocessors from Intel existed only as block diagrams, but Four-Phase had a working computer system built around the AL1 chip. Boysel asserted in the article:

> The computer on a chip is no big deal. It's almost here now. We're down to nine chips and we're not even pushing the state of the art. I've no doubt that the whole computer will be on one chip within five years.[25]

In fact, being in the computer business gave Boysel reason to be quiet about the AL1. While there was no reason to believe that a sale would

Figure 6. Early ad for Four-Phase Systems Model IV/70, circa 1970. The following page states 'then: You'd have System IV/70—the data base access system of the 70s.' Note that the advertisement only mentions the IV/70 having 'the whole 75,000 component CPU on one card.' The top circuit card above '2' is the CPU card, with a random logic chip and ROM chips. The lower circuit card is the memory card, which used Four-Phase's 1K RAM chips. Courtesy, Lee Boysel.

hinge on exactly how much of the central processing unit Four-Phase had put on one integrated circuit, the AL1 was one of Four-Phase's most valuable pieces of intellectual property and were other companies to copy it, they could conceivably offer a competitive product. Four-Phase refused to sell the AL1 to a manufacturer of computer terminals, believing that such a sale would jeopardize its computer business, which it considered more profitable than the semiconductor business.[24]

Even when Four-Phase did want to talk about the advanced semiconductor technology in its systems as a means of promoting sales, there were other things besides the AL1 to point to. Four-Phase produced one of the first computer systems equipped with MOS semiconductor memory in place of magnetic cores. Semiconductor memories had been the subject of much discussion and work in both the semiconductor and computer industries, which would make it easier for customers to understand the significance of Four-Phase's achievement. An article by Boysel and two colleagues on Four-Phase's semiconductor memory was the cover story in *Electronics*, the leading trade journal in the industry.[25]

Four Phase's position in the computer industry also shaped the way the AL1 was packaged. A traditional constraint in the packaging of integrated circuits was in the number of inputs and output pins on the package. In the late 1960s low-cost dual-inline-packages (DIPs) were available with 16 or 18 pins. For an eight-bit processor, the use of such packages would mean that there were more input and output signals than there were pins on the package. One solution to this problem was to have some signal lines share pins, which slowed down the system. Another alternative was to use a very expensive 40-pin package. Costs for such a package were so high (around five dollars each), that they represented a greater cost than making the integrated circuit itself.[26]

Intel put the 8008 in an 18-pin DIP and multiplexed the signals. It had used these packages for its memory chips and they were cheap. Intel, as would be expected of a semiconductor producer, was highly resistant to using an expensive purchased package that would put a majority of the cost of the component outside of its control. The AL1 was put in a 40-pin DIP. For a computer systems company, building a computer that would have a purchase price of ten thousand dollars or more, the few extra dollars paid for high pin count packages were more than made up for in increased performance. Intel's next generation microprocessor, the 8080, did come in a 40-pin DIP, after customers complained that the 18-pin DIP hobbled the 8008's performance, and after package prices came down.[27]

For all Intel's talk about a computer on a chip, the 8008 required many ancillary chips to convert voltage levels so it could interface with other subsystems, such as memory. In spite of what Intel advertising might say, the 8008 was not part of an integrally designed system, it was an opportunistically designed part. No such interface circuits were required with the AL1, for the whole system was designed together. Again, in its second generation microprocessor, Intel fixed this after receiving complaints from customers.[28]

One of the ways the AL1 got its speed was through the use of four-phase logic, a very sophisticated type of circuitry, which had used four clock signals applied to the chip in a very close relationship. This required special clock circuits off the chip and a very knowledgeable user, who could control the parameters of the entire system, such as wiring lengths, to assure the system would work. Intel did not use four-phase logic, and the 4004 and 8008 could tolerate a much less sophisticated user.[29]

The Microprocessor: an Innovation in the Semiconductor Industry

The idea here is not to substitute the name of Lee Boysel for Ted Hoff as the inventor of the microprocessor, but to suggest that the AL1 can provide a different perspective on the invention of the microprocessor. Eric von Hippel has written that an innovation often occurs in the industry that stands to benefit the most from it. Here we have something analogous with respect to what constitutes an invention. [30] Looking at Four-Phase and Intel, similar integrated circuits were being made in both firms, one in the computer industry and one in the semiconductor industry, but only the semiconductor company called it an invention. The economics of the semiconductor industry gave what we call the microprocessor a completely different meaning than it had in the computer industry.

Perhaps not unrelatedly, a number of Hoff's contemporaries who were outside the semiconductor industry and familiar with computers have not been much impressed with the microprocessor as an invention. Carver Mead, a professor of electrical engineering at Caltech working on applications of digital electronics, called it a 'no-brainer.' Researchers from IBM claimed that they did not consider the Intel work an invention at all. In a manual written in 1968, before Intel had done anything, one IBM researcher wrote 'hopefully the day of the "computer on a slice" is nearly dawning.' [31] It was, but it did not dawn at IBM; it rose in the west first. The IBMers knew something like a microprocessor could be made, but they had no incentive to do it. It made little difference to a computer company whether the central processing unit function was put on one integrated circuit or on several. For something like a computer-on-a-chip to be significant to a computer company, there would have to be additional innovations which would make new computer systems possible.

To Intel however, the microprocessor was an innovation that was a solution to a real problem. Gordon Moore and Robert Noyce had founded Intel as a company that would concentrate on standard Large Scale Integration (LSI) products. The possibility of putting many transistors on an integrated circuit raised what became known as the part-number-problem. When each integrated circuit contained only one or two logic circuits, it was possible to build up a large digital system from these primitives using only a handful of different chip types. But when each chip contained upwards of a hundred logic circuits as envisioned in LSI, each chip became confined to a specific application in a specific system. Since the number of circuits in a system was still large compared to the one hundred on a chip, a system built using LSI would be made up of many chips, and also many different chip part numbers. Across different systems, there would be very little commonality, so that part numbers could not be shared. This explosion of part numbers, where the semiconductor plant would have to make small quantities of numerous chip designs, threatened to undermine any economic advantage that accrued by moving to higher levels of integration.[32]

In the late 1960s, three approaches to building LSI chips existed: computer-aided-design, custom, and standard. Under computer-aided-design, the semiconductor company would develop an infrastructure that customers would use to do the design work themselves. Automation would allow a semiconductor company economically to produce a large number of different part numbers in small volumes. Moore had had a large computer-aided-design program underway at Fairchild, but he developed doubts about it shortly before he left to form Intel. In its early days, Intel made no efforts in this area.[33]

The custom approach involved dealing with the part-number problem on a case by case basis. A semiconductor company would contract to design a specific part for a specific company. For such an approach to work, the parts had to have high volumes. The problem with this approach was that it required the semiconductor company to have a large number of designers, and potential customers could be very fickle. After the semiconductor company had put a great deal of effort into the design of a part, the customer's requirements might change and the order vanish.[34]

The last approach was standard parts. The semiconductor company would design parts which it believed had general applicability and offer them for sale to all comers. This approach could lead to large production volumes for every part, and would require few circuit designers. One disadvantage of this approach was that it could expose the company to competition as other firms moved in to make a popular part.

As they started Intel, Moore and Noyce believed that standard parts were the only economically viable way to proceed with LSI. At the 1966 Fall Joint Computer Conference session considering large scale integration Robert Noyce—still at Fairchild—spoke of the cost advantages of standard parts, and asserted that how far the industry accepted standardization 'may well determine whether or not large arrays [i.e., LSI] are used in significant quantity in the future.' While Noyce noted that at the time the only standard LSI arrays in existence were memories and shift registers, he also prophesied that '[t]he appearance of more standard arrays seems inevitable.' In the spring of 1970, before Intel's first microprocessor had been implemented, Robert Noyce spoke at the IEEE annual convention on trends in silicon technology. He noted Moore's law (the doubling of the number of components on a chip every year), but asserted that one of the major potential limitations of silicon integrated circuits was an economic one. He claimed that 'finding high volume "universal" high complexity circuits will be difficult,' and 'failing in this quest, the fabrication costs become secondary to the costs of design and tooling,' resulting in a lack of motivation to produce more complex integrated circuits.[35]

Intel was started by Moore and Noyce as a company to make standard LSI products, and its early work was in memories because they were the ones then in existence.[36] But Noyce and Moore were predisposed to embrace the idea of a processor on a chip, because of its potential as a standard part. Much of the writing on the microprocessor has focused on Ted Hoff's genius, or how credit should be apportioned between Hoff and the other Intel engineers, while ignoring the larger issue of corporate strategy.[37]

The microprocessor gave Intel access to the largest market for digital integrated circuits, logic, on its terms. Intel's core strength was in semiconductor processing technology and it was founded on the premise that it could gain a competitive advantage through the development of a new process that would allow for the fabrication of very complex integrated circuits. Intel could thereby stay out of the market for simple small scale integration circuits, which were commodity parts subject to vicious price wars. But prior to the microprocessor, Intel's commitment to LSI excluded it from the market for digital logic, because no standard LSI logic parts existed. Most digital logic applications required much less than a full general purpose computer and were made up of many small scale integration Transistor-Transistor Logic (TTL) integrated circuits. With the introduction of the 4004 and 8008, Intel proposed that its customers reparse their systems to replace many cheap integrated circuits (made by someone else) with a few high priced integrated circuits (made by Intel). In an August 1972 ad Intel claimed that its 4004 could typically replace 90 TTL circuits, while the 8008 could replace 125.[38]

The important fact about Intel's microprocessor was not that it was a computer-on-a-chip, but that it was generalizable and could aggregate demand. Based on this, the trajectories of Boysel's AL1 and Intel's microprocessors greatly diverged. Intel's microprocessors could be used for a wide variety of things. Intel and its consultants came up with a notebook full of possible applications. The applications of the microprocessor were not at all limited by what Intel engineers could conceive. A frequent occurrence at Intel's microprocessor seminars was for a participant to come up afterwards and present an Intel engineer with a new way of using the chip. The typical response was, 'I hadn't thought of that, but yeah it would work.'[39]

The most dramatic example of how the microprocessor was not limited to uses Intel supported comes with the personal computer. Gordon Moore conceived of a personal computer as one possible application early in the history of the microprocessor, but he ultimately rejected it as a bad idea. The only use he could think of for it was as a place for housewives to keep recipes.[40] Of course that did not mean that no one could attempt to build a personal computer with an Intel microprocessor, and others did.[41]

On the other hand, while the AL1 had the architecture of a general purpose computer, making it capable of being used in a variety of applications, it was under the complete control of Four-Phase and it could only be used as one third of the Arithmetic Logic Unit of a Four-Phase system unless Four-Phase decided otherwise. It is probably fair to say that few of Four-Phase's customers even knew (or cared) that such a thing as an AL1 even existed. While they could come up with new uses for an entire Four-Phase system, they could not come up with new applications for the AL1. Any innovations in how the AL1 would be used had to come from Four-Phase itself. And while Boysel was an extremely creative person, he had his hands full running the company.

Four-Phase's position in the computer industry further constrained the proliferation of the AL1 chip. In the early 1970s, while the semiconductor industry was not capital intensive, the computer industry was, due to the way medium to large-sized computers were acquired. Following a pattern that had been set in the pre-computer office equipment era, most computers were leased, not bought. This meant that every computer that Four-Phase made was a capital item, which would only gradually pay for its costs over the course of its lease. Four-Phase had to raise funds, either debt or equity, to pay for every computer it made. Leasing acted as a rein on the growth of a start-up, for the capital requirements would strangle the company if it were to grow too quickly. By 1974, the company's first full year of profitability, Boysel had had to raise twenty-seven million dollars to keep it going.[42]

Leasing made Boysel, at heart a technological radical, more conservative. Each new model that Boysel introduced threatened his installed lease base. Four-Phase's conservatism can be seen in its use of semiconductor technology. Four-Phase was able to quickly produce enough chips to meet its requirements into the foreseeable future. Production was halted and the chips were stored for later use. Such action would have been inconceivable in the semiconductor industry, where a part's value only went down over time. But at Four-Phase the value of the chips was related to the lease price Four-Phase could get for its systems, which remained relatively constant over time. While the semiconductor industry had a highly elastic demand for its chips, Four-Phase faced an inelastic demand; even if its chips could be produced for nothing, the intricacies of lease financing would determine how many systems Four-Phase would build.

Although it never became the size of IBM, or even Digital Equipment, Four-Phase achieved a substantial level of success with its approach. Its systems were widely used by hospitals to handle billing as well as by government agencies for data entry. Although Four-Phase Annual Reports made constant reference to the continual need for capital (i.e. bank loans) required in the computer leasing business, Four-Phase stayed in the good graces of the banks and financial markets. In 1979 the firm had revenues of $178 million and net income of $16 million. In 1982, in the face of increasingly aggressive competition from IBM, Four-Phase was sold to Motorola in an exchange of stock valued at $253 million.[43]

Conclusion

Nathan Rosenberg's classic article on the machine tool industry reminds us that innovations may be more likely to enter the economy through a particular door (or industry). Here that door was the semiconductor industry. For although they looked similar at the block diagram level, the AL1 was an answer to a specific problem; Intel's microprocessor could respond to a range of generalizable problems.[44]

Lee Boysel's comment in 1970 that the 'computer on a chip was no big deal' was only half right. Many people had seen it coming, and for a computer company that made its own semiconductors, it was of little moment whether the central processing unit was on one chip or two or three. But for a semiconductor company such as Intel, what it called the computer on a chip had great import. It offered a way for Intel to get into markets previously denied it, and to bring electronics into a wide new range of areas. Gordon Moore stated that it allowed Intel to 'make a single microprocessor chip and sell it for several thousand applications.' In 1975 Robert Noyce was calling Intel 'the world's largest computer manufacturer.'[45] It would take years before that was manifest to the rest of the world.

Notes

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2. For Texas Instrument's patent suits in the 1990s, see *New York Times* (11 September 1990), p. D4; (9 March 1993), p. D18; (28 April 1993), p. D4. The suits were settled out of court. For a discussion of the Texas Instruments microprocessor patent, see Michael S. Malone, *The Microprocessor: A Biography* (New York, 1995), pp. 13–14, 130–132. In an example of the shifting connections common in Silicon Valley, the work on the AL1 as microprocessor was coordinated by an intellectual property firm whose chief technical officer was Ted Hoff, the putative inventor of the microprocessor.

3. Lee Boysel, 'Court Room Demonstration System, 1969 AL1 Microprocessor,' (3 April 1995) (in author's possession); Lee Boysel, 'AL1 Microprocessor Demonstration Model,' (27 February 1993) (in author's possession).
4. Looking at how technologies are shaped differently in different industries is compatible with Pinch and Bijker's social construction of technology and may be a way of synthesizing business history and the history of technology. Trevor J. Pinch and Wiebe E. Bijker, 'The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other,' in Wiebe E. Bijker, Thomas P. Hughes, and Trevor J. Pinch (eds.), *The Social Construction of Technological Systems*, (Cambridge, MA, 1987), pp. 17–50. For a summary of the state of the relationship between business history and the history of technology, see David A. Hounshell, 'Hughesian History of Technology and Chandlerian Business History: Parallels, Departures and Critics,' *History and Technology* 12 (1995), 205–24. For a study examining how the determination of what constitutes an invention is socially constructed, see Carolyn C. Cooper, *Shaping Invention: Thomas Blanchard's Machinery and Patent Management in Nineteenth-Century America* (New York, 1991).
5. For a study of Silicon Valley that takes an ecological approach, see AnnaLee Saxenian, *Regional Advantage: Culture and Competition in Silicon Valley and Route 128* (Cambridge, 1994). For other work on Silicon Valley, see Robert Kargon, Stuart W. Leslie, and Erica Schoenberger, 'Far Beyond Big Science: Science Regions and the Organization of Research and Development,' in Peter Galison and Bruce Hevly (eds.), *Big Science: The Growth of Large-Scale Research*, (Stanford, 1992); Stuart W. Leslie and Robert H. Kargon, 'Selling Silicon Valley: Frederick Terman's Model for Regional Advantage,' *Business History Review* 70 (Winter 1996), 435–72; Robert Kargon and Stuart Leslie, 'Imagined Geographies: Princeton, Stanford, and the Boundaries of Useful Knowledge in Postwar America,' *Minerva* 32 (Summer 1994), 121–43; Everett M. Rogers and Judith K. Larsen, *Silicon Valley Fever: Growth of High-Technology Culture* (New York, 1984); Michael S. Malone, *The Big Score: The Billion Dollar Story of Silicon Valley* (Garden City, 1985).
6. For a more detailed discussion of both the MOS transistor and Fairchild's work on it in the 1960s, see my dissertation, 'New Technology, New People, New Organizations: The Rise of the MOS Transistor, 1945–1975' (PhD dissertation, Princeton University, 1998).
7. Among the most prominent members of the R&D MOS group who left were Andy Grove, chief executive officer at Intel from 1987 to 1998, and Les Vadasz, as of April 1999 a senior vice-president and member of the board of directors. Some of the most research oriented of the Fairchild MOS group were either not invited to join Intel, or did not want to leave the R&D environment. Fairchild R&D had another branch of its MOS effort, which was developing a computer-aided-design system. Moore had lost faith in this work and did not continue it at Intel. Consequently no one from this group moved to Intel. In 1980, the key figures from this program started LSI Logic, which used computer-aided-design to build application specific integrated circuits. Rob Walker with Nancy Tersini, *Silicon Destiny: The Story of Application Specific Integrated Circuits and LSI Logic Corporation* (Milpitas: CMC Publications, 1992).
8. Gordon Moore, interview with author, 15 May 1996; Lee Boysel, interview with author, 23 January 1996. I have not been able to get an organization chart that shows the exact relation between the two groups.
9. A shift register is a memory element that stores data serially. For more on Wanlass and his role in the transfer of MOS technology, see Chapters 1, 4, and 5 of my dissertation.
10. Lee Boysel, interview with author, 23 January 1996; Lee Boysel, interview with author, 28 February 1997.
11. Gordon Moore recalled Boysel's secretiveness, remembering in particular being annoyed at one meeting where Boysel presented the completed design for a part that no one was even aware he was working on. Moore also acknowledged that Boysel had a better sense of how MOS technology could be used than anyone in R&D did. Gordon Moore, interview with Ross Bassett, 15 May 1996; Gordon Moore, interview with Ross Bassett and Christophe Lecuyer, 18 February 1997.
12. Lee Boysel, untitled document (13 September 1967) (in author's possession). The block diagram is reproduced on page 248 of my dissertation.
13. Ibid. For examples of work on MOS calculators, see *Electronic News* (21 September 1964), p. 8; Lewis H. Young, 'Uncalculated Risks Keep Calculator on the Shelf,' *Electronics*, 6 (March 1967), 231–34.
14. Those involved in Fairchild's initial development of integrated circuits knew the resistance a semiconductor manufacturer could meet when it tried to encroach on territory occupied by computer

designers. Gordon Moore related what happened when Fairchild went to one customer with its integrated circuit flip-flop, the basic storage element in a computer. According to Moore, the customer's reaction was:

> This is ridiculous. We need 16 different kinds of flip-flops. We have 16 engineers, each one of them a specialist in these flip-flops. There is no way we can use that single design for anything. It's a crummy flip-flop in the first place and it's not specialized for the things we need.

The customer's arguments ended when Fairchild offered to sell their flip-flop for much less than the costs of the components that made up a flip-flop. Gordon Moore, interview by Allen Chen, 6 January 1993, Intel Museum, Santa Clara, California.

15. John Hulme, Boysel's manager at Fairchild, had such a hard time communicating with Boysel that he considered him to be virtually in another company. Hulme also noted that some at Fairchild were suspicious of Boysel's motives. John Hulme, interview with author, 16 November 1996. Lee Boysel, interview with author, 23 January 1996; Lee L. Boysel, 'Memory on a Chip: A Step Toward Large-Scale Integrarion,' *Electronics* 6 (February 1967), 93–97; Lee L. Boysel, 'Adder on a Chip: LSI Helps Reduce Cost of Small Machine,' *Electronics* 18 (March 1968), 119–21; Lee L. Boysel and Joseph P. Murphy, 'Multiphase Clocking Achieves 100-Nsec MOS Memory,' *EDN* 10 (June 1968), 50–53; Fairchild Semiconductor, *MOS/LSI* (Mountain View: Fairchild Semiconductor, 1968).
16. Lee Boysel, inrerview with author, 28 February 1997; Lee Boysel, interview with author, 23 January 1996; John Hulme, interview with author, 16 November 1996. One reason Boysel was not sued by Fairchild, was the turmoil it was in at the time. In July 1968, Fairchild hired Lester Hogan from Motorola as president, who then brought a management team with him from Motorola. Motorola then sued Fairchild. Many Fairchild employees became disgruntled with the new management and left. In the resulting disarray Boysel's work may have been forgotten or not fully appreciated by the managers from Motorola.
17. Blyth & Co. 'Confidential Report on Four-Phase Systems, Inc.' (30 April 1971); Lee Boysel, interview with author 28 February 1997. Corning had an agreement with Boysel that if his company failed, he and his engineers would join Signetics.
18. Lee Boysel, interview with author, 28 February 1997. Four-Phase's early work is described in Marge Scandling, 'A Way to Cut Computer Costs?' *Palo Alto Times* 28 (April 1969), 9.
19. The relation between Four-Phase and Cartesian, which would now be called a silicon foundry, is an early example of the blurring of boundaries between firms that AnnaLee Saxenian has noted as a distinctive characteristic of Silicon Valley. Saxenian, *Regional Advantage*, pp. 29–57. Cartesian, Inc. 'Prospectus' (nd), in author's possession. While they were both at Fairchild, Cartesian's founder quoted Boysel prices per processed wafer which provided the basis for Four-Phase's early plans. These prices were hand written on a sheet of yellow paper. [Bob Cole] 'Price Per Wafer per design per order' (nd), in author's possession.
20. '"Intelligent" IV-70 Outguns IBM's 2260s and 3270s,' *Computerworld* 23 (June 1971), 26; Four-Phase Systems, Inc. 'Preliminary Prospectus' (30 May 1973).
21. Lee L. Boysel and Joseph P. Murphy, 'Four-Phase LSI Logic Offers New Approach to Computer Designer,' *Computer Design* (April 1970), 141–146. In fairness, when Intel introduced what is now known as a microprocessor, it did not have a stable name. The first thing Intel made that it called a microprocessor was a circuit board with a number of integrated circuits—this was a microprogrammed processor. Intel's early advertising called the 4004 both a computer on a chip and a microcomputer, but not a microprocessor. Because Intel was selling the 4004, it had to have a clear descriptive name for it, in a way Four-Phase never had to with the AL1. M. E. Hoff, Jr. and Stanley Mazor, 'Standard LSI for a Microprogrammed Processor,' *1970 NEREM Conference Record*, 92.
22. This paper will not cover the details of Intel's early microprocessor work. This has been addressed by participants, journalists, and historians in numerous papers and books. Federico Faggin, Marcian E. Hoff, Jr., Stanley Mazor, and Masatoshi Shima, 'The History of the 4004,' *IEEE Micro* (December 1996), 10–20; Tekla S. Perry, 'Marcian E. Hoff,' *IEEE Spectrum* (February 1994), 46–49; Robert N. Noyce and Marcian E. Hoff, Jr., 'A History of Microprocessor Development at Intel,' *IEEE Micro* (February 1981), 8–21; Federico Faggin, 'The Birth of the Microprocessor,' *Byte* (March 1992), 145–50; Stanley Mazor, 'The History of the Microcomputer: Invention and Evolution,' *Proceedings of the IEEE* 83 (December 1995), 1601–8; Malone, *The Micoprocessor: A Biography* pp. 3–20; William Aspray, 'The Intel 4004 Microprocessor: What Constituted Invention?' *IEEE Annals of the History of Computing* 19 (1997), 4–15.

23. Elizabeth de Atley, 'LSI Poses Dilemma for Systems Designers,' *Electronic Design* (1 February 1970), 44–52.
24. Four-Phase's advertising materials either did not mention anything about the AL1 or discussed it in general terms, such as putting 'the whole 75,000 component CPU on one card.' Four-Phase Systems, 'System IV/70: The Data Base Access System of the 70's' (8 January 1970) (in author's possession); Four-Phase Systems, 'Announcing System IV/70: The Data-Base Access System of the 70's' (no date), in author's possession.
25. Lee Boysel, Wallace Chan, and Jack Faith, 'Random-access MOS memory packs more bits to the chip,' *Electronics* (16 February 1970), 109–115. For the general environment regarding semiconductor memories, see pages 361–68 of my dissertation. I have not done the research to enable me to say that Four-Phase produced the first computer with an all semiconductor memory, but contemporaries generally accepted Four-Phase's claims in that regard. IBM ran an advertising campaign claiming its 370/Model 145 was the first computer with semiconductor memories. At an industry trade show, Four-Phase displayed modified versions of the IBM advertisements, claiming priority in semiconductor memory computers. *Electronic News* (12 October 1970), 57; Lee Boysel, interview with author, 23 January 1996.
26. Lee Boysel, interview with author, 28 February 1997; Lee Boysel, interview with author, 23 January 1996.
27. Hal Feeney, interview with author, 23 April 1997. Four-Phase's position in relation to Intel in semiconductor packaging, was similar to that of IBM compared with the semiconductor industry. IBM was willing to put much more money and effort into packaging than those in the semiconductor industry were. For a statement of the emphasis IBM as a computer company put on packaging, see Steven W. Usselman, 'IBM and its Imitators: Organizational Capabilities and the Emergence of the International Computer Industty,' *Business and Economic History* 22 (Winter 1993), 1–35.
28. Federico Faggin, 'The Birth of the Microprocessor,' *Byte* 17 (March 1992), 150.
29. Joel Karp and Elizabeth DeAtley, 'Use Four-phase MOS IC Logic,' *Electronic Design* 7 (April 1, 1967), 62–66. In Boysel's testing of the 1993 'microprocessor' version of the AL1 running a CTC application (the original user of the Intel 8008), the AL1 performed from 20 to 50 times faster than the 8008. Lee Boysel, 'AL1 Microprocessor Demonstration Model' (27 February 1993) (in author's possession). Although this paper stresses the differences between Intel and Four-Phase, there were connections. By going into standard LSI parts, (RAM, ROM, and larer microprocessors) Intel was designing parts much like those Boysel had built at Fairchild. Robert Noyce was on the board of directors of Four-Phase and would have known the details of Four-Phase's work (and presumably taken it back to Intel). Blyth & Co., 'Confidential Report on Four-Phase Systems, Inc.' (20 April 1971) (in author's possession).
30. Eric von Hippel, *The Sources of Innovation* (New York, 1988).
31. D. L. Critchlow, R. H Dennard, S. E. Schuster, and E. Y. Rocher, 'Design of Insulated-Gate Field-Effect Transistors and Large Scale Integrated Circuit Chips for Memory and Logic Applications,' (4 October 1968) (in author's possession), 218. On Mead's reaction to the microprocessor, see Joyce Gemperlein and Pete Carey, 'If Hyatt Didn't Invent the Microprocessor, Who Did?' *San Jose Mercury News West* (2 December 1990), 25. For Mead's ideas at that time, see Carver Mead, 'Computers That Put the Power Where it Belongs,' *Engineering and Science* (February 1972), 4–9. For the IBM response, Dale Critchlow, note to author (19 July 1995).
32. In 1967 two researchers at IBM estimated that with LSI the industry might require as many as 100,000 unique part numbers. M. G. Fubini and M. G. Smith, 'Limitations in Solid-State Technology,' *IEEE Spectrum* (May 1967), 55–59.
33. Rob Walker with Nancy Tersini, *Silicon Destiny: The Story of Application Specific Integrated Circuits and LSI Logic Corporation* (Milpitas: CMC Publications, 1992); Gordon Moore, interview with author, 15 May 1996.
34. Intel's own brief experience with custom work shows its problems. It designed the 4004 in response to a request from Busicom, but Busicom never became a major customer, agreeing to give Intel greater rights to market the part in exchange for being relieved of obligations in the contract. Intel's 8008 was designed in response to a request from CTC which backed out of the project before it was completed.
35. Robert N. Noyce, 'Integrated Silicon Technology in the '70's,' *IEEE 1970 International Convention Digest*, 171; Robert N. Noyce, 'A Look at Future Costs of Large Integrated Arrays,' *FJCC* (1966), 111–114. Another former Fairchild manager expressed similar views. In 1968 Charles Sporck, the former general manager at Fairchild, who was by then the head of National Semiconductor said,

'Custom work kills a company when it's trying to grow. Henry Ford's Model T approach is just as valid now as it was then.' Quoted in Don C. Hoefler, 'Nat'l Semicon's Sporck Sees Firm Gaining Ground,' *Electronic News* (16 December 1968), 49.

36. The apparent irony is that Intel's microprocessors came from custom work for Busicom and CTC. But Intel had the strategy of using custom work to create standard parts. In 1970, Robert Noyce stated:

    Intel is actively soliciting custom business. We're doing this because we want to learn by working very closely with customers what they need to do their job. Hopefully by working with several customers in the same area, we can find the commonality that everybody seems to need, and then we can build that as a standard part. And once it exists as a standard part, the cheapest way for a guy to go will be to use it, because he will have all the advantages of a production line flow that is already established. quoted in Elizabeth de Atley, 'Can you build systems with off-the-shelf LSI?' *Electronic Design* 5 (March 1, 1970), 50.

37. Malone, *The Microprocessor: A Biography*, 3–20; William Aspray, 'The Intel 4004 Microprocessor: What Constituted Invention?' *IEEE Annals of the History of Computing* 19 (1997), 4–15. In interviews discussing the microprocessor, Ted Hoff has sometimes presented himself as the lone inventive genius, who had to struggle mightily to convince others of the worth of his invention, particularly those in marketing. But Gordon Moore claims that Hoff was under a misapprehension about who he needed to convince and claims to have immediately recognized the significance of Hoff's idea. Ted Hoff, interview with Rob Walker, Stanford University Library, Stanford University; Gordon Moore, interview with Rob Walker, Stanford University Library, Stanford University. Gordon Moore, interview with Ross Bassett and Christophe Lecuyer, 18 February 1997.
38. *Electronic News* (7 August 1972), 24.
39. Hal Feeney, interview with author.
40. Gordon Moore, interview with Stein, 17 October 1983, Intel Museum, Santa Clara, CA.
41. Paul Ceruzzi, 'From Scientific Instrument to Everyday Appliance: The Emergence of Personal Computers, 1970–1977,' *History and Technology* 13 (1996), 1–31.
42. Lee Boysel, 'The Way it Really Was,' 24 May 1974 (in author's possession). For a discussion of the effect of computer leasing on the computer industry see Katherine Davis Fishman, *The Computer Establishment* (New York, 1981), pp. 15–18; Franklin M. Fisher, John J. McGowan, and Joen E. Greenwood, *Folded, Spindled, and Mutilated: Economic Analysis and U.S. vs. IBM* (Cambridge, MA, 1983), pp. 191–96. Since the 1980s, the computer and semiconductor industries have switched, with the semiconductor industry so capital intensive as almost to preclude new entrants, while college students have started computer companies.
43. On the cover of its 1976 *Annual Report* Four-Phase had a Social Security operations center using its systems and asserted that the agency had acquired 1300 Four-Phase terminals. Four-Phase Systems, Inc., *Annual Report 1976*, pp. 1–2; Four-Phase Systems, Inc., *Annual Report, 1980*; *Wall Street Journal* (11 December 1981), p. 56; (4 January 1982), 33; (3 March 1982), p. 44.
44. Although those responsible for managing IBM in the 1980s and early 1990s have been pilloried for their performance, the case of Four-Phase may suggest why it took IBM so long to accommodate itself to the microprocessor. The economics were quite different for it as a vertically integrated producer of semiconductors that sold computers than they were for Intel. Although IBM has had microprocessor projects underway since roughly the time of Intel's initial work, the microprocessor has only relatively recently had a major role at IBM. (Now IBM sells semiconductors on the open market and has economic considerations closer to those of a semiconductor company.) For some of IBM's problems in this regard, see Charles H. Ferguson and Charles R. Morris, *Computer Wars: The Fall of IBM and the Future of Global Technology* (New York, 1994), pp. 30–97.
45. Gene Bylinksy, 'Here Comes the Second Computer Revolution,' *Fortune* (November, 1975) 184. One of the ironies associated with Intel is that although its staff consisted mainly of experts in semiconductor processing with very little computer expertise, it was able to transform itself into a computer company. But even today those roots are clear. All of Intel's chief executive officers as well as many senior managers have had backgrounds in semiconductor processing rather than computers.