4. Fourth case study – the silicon chip

Ian Pollock
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Fig. 4.1 Andy Grove – CEO of Intel and author of *Only the paranoid survive*

4.1 Introduction

The development of the transistor in the middle of the twentieth century, described in the previous chapter, provided an example of innovation in its Schumpeter A-phase. By the beginning of the 1960s, however, its manufacturing process had stabilised – epitaxial deposition of semiconductor materials and planar diffusion of dopants were used universally for device fabrication. The concept of the integrated circuit had been demonstrated to be feasible. The path of development was clear. New devices would, for the foreseeable future, continue to become smaller and their complexity would increase (Moore's Law). As a result, unit costs would decrease and this would permit electronics-based industries to expand.

The final case study follows what may be regarded as the Schumpeter B-phase of the transistor, the development of the silicon integrated circuit, exemplified by the progress of the bell-wether company, Intel, which was responsible for the introduction of semiconductor-based memory circuits for computers and the microprocessor – two major innovations which resulted in massive expansion of the global economy.

The review starts with the setting up of the company at a time when the manufacturing technologies were well-established industry standards. It follows Intel through the travails of free competition and marks the key events on the path to becoming industry leader. Initially, many companies – Texas Instruments, Fairchild, Motorola, Signetics, ITT and Philips are just a random selection – possessed the potential and the will to succeed in the industry. One by one they fell by the wayside on the path to the summit, as did the many individual entrepreneurs who participated in the development of the incandescent lamp.

Although many of the factors which contributed to Intel's success may be regarded as felicitous, the narrative highlights how chance events were turned to advantage by the "prepared mind" of its management. Of particular note are the initial use of scarce resources, the exploitation of threats to opportunities, the creation of luck, the transformation of finances, the change in utilisation of intellectual property rights, the exploitation of the legal process and the adroit political management of competition law.

4.2 The house that Gordon and Bob built

> "If you wanted to do wonderful things, Intel was the place to be"
> **Federico Faggin** speaking to David Manners
> *Electronics Weekly* 18 Sep 1996

The technology of very large scale integration (VLSI) was mostly, this was either in the public domain or could be readily acquired from specialist equipment suppliers. The history of the commercial development of the industry is, however, dominated by Intel Corporation which grew to be the industry giant.

The diaspora which led to the foundation of Intel began with the defection of William Shockley from Bell Telephone Laboratories. With the encouragement of Arnold Beckman, founder of Beckman Instruments, he returned to his native orange groves of Palo Alto in California, to set up Shockley Transistor Corporation. Shockley gathered around him a group of able young semiconductor physicists and engineers. However, although he had a brilliant analytical mind, he was a poor manager of people, committing such *faux pas* as posting their salaries on the communal notice board and subjecting an engineer to a lie detector test on the suspicion that the explanation for a slow-moving project was that someone was sabotaging it.

After a couple of years, eight of his team could tolerate him no longer and, led by Robert Noyce, decided to quit. The 'Traitorous Eight' obtained funding from Sherman Fairchild to set up a subsidiary of his Fairchild Camera and Instrument Corporation. In return for an investment of $1.5m, Fairchild acquired an option to buy them out for $300,000 each if the operation proved successful.

In 1959, shortly after the invention of the planar transistor by Noyce and Hoerni, Fairchild's company exercised its option. Although the eight founders remained at Fairchild Semiconductor, they no longer had any real influence. Control moved to the parent company in Syosset, New York. Boredom set in and gradually the pioneers left to establish fresh companies. Eventually, Gordon Moore and Robert Noyce decided there was no future with Fairchild and approached Arthur Rock, the venture capitalist who had brokered the deal to set up Fairchild Semiconductor. It took a very short time to raise the cash and Intel came into being on 16 July 1968, with Rock as chairman. **Jackson 1997, p9**

Once the company was set up, there was a veritable flood of scientists and engineers who wanted to joint the new enterprise. Moore created a flat organisation structure with short lines of communication. For flexibility there were no offices and the company parking lot operated on a first-come, first-served basis with no reserved places. Employees were locked into the company with a succession of stock options – with a rising share price, these "golden handcuffs" meant that it was impossible to leave without incurring a large financial penalty.

An early and crucial appointment was Andy Grove, a Hungarian emigré who became the third member of the ruling troika. Grove proved to be the driving force which propelled Intel to leadership of the semiconductor industry.

4.3 Launch products

From the outset, Intel was driven by market pull. The computer industry provided the engine and the target product was the memory units which stored data temporarily during the calculations. At the time, this function was provided by magnetic stores, which were constructed from matrices of tiny rings of ferrite material. These were threaded with copper wires which changed the direction of magnetisation according to whether the data to be stored was a zero or one. Fabrication was expensive and the devices stored only a limited amount of information due their physical size, although they consumed relatively large amounts of electrical power. Noyce and Moore surmised that, if a suitable semiconductor device could be made to perform this function, the world's computer manufacturers would beat a path to their door.

There were three possible ways of fabricating this device. One employed field-effect transistors based on metal-oxide-semiconductor (MOS) technology. Another utilised multichip memory modules and the third was based on bipolar devices using Schottky junctions. Initially, Moore and Noyce decided that they would pursue all three to increase the chances of success. The selection of the one to go into production was postponed until the pros and cons of each solution became clearer. Others were aware of this potential market. A race was therefore on, to be the first to produce a device with suitable characteristics.

4.3.1 The DRAM

In its early days, Intel relied heavily on contract projects to pay for its research and development. An early customer for Intel's memory chips was Honeywell, one of the 'Seven Dwarfs' of the computer industry which was trying to steal a march on the market leader 'Big Blue' (IBM). Honeywell wanted to pre-empt its competitors in the substitution of semiconductor memory for magnetic core. It intended to incorporate a 64-bit semiconductor scratchpad memory in a new range of machines to be launched in 1969 and 1970 and invited several firms, including Intel, to compete for this business. Honeywell offered a contribution of $10,000 towards the funding of the development, but a far more attractive inducement was the prospect of a sale 10,000 units at $100 each. Intel developed a chip, the 1102, which met the specification and had samples by the spring of 1969. It won the order and the new product launched it on the path to commercial success.

Whilst working on the chip for Honeywell, Intel produced a development, the 1103, which had the ability to store 1024 bits on a single chip and offered the capability of meeting one of the computer industries goals – storage at less than a penny a bit. Intel achieved this by inventing a new memory architecture, dynamic random-access memory (DRAM) which enabled the device manufacturer to pack four times as many devices on to a single chip. The cost of this improvement was that the data storage was transient and therefore the memory contents had to be refreshed every millisecond. The trade-off was that the addition of relatively cheap extra power supply permitted an order of magnitude increase in performance of expensive memory.

4.3.2 The EPROM

One of Intel's device physicists, Dov Frohman, was assigned the task of investigating failure mechanisms in faulty circuits. [Jackson 1997, p92] He surmised that a possible reason that the silicon-gate devices had failed might be that some of the gates in the circuit had become disconnected, or 'floating'. During the course of his investigation, Frohman found that the failure was due to break in the connection to the silicon gate in some of the field-effect transistors. He discovered that an electric charge impressed on these gates was stored and could be utilised as a programmable memory device. An array of these floating gate transistors could store a sequence of bits and perform the same function as a read-only memory (ROM) chip. A conventional ROM needed special equipment to program it as the operation was performed by fusing special links which were installed when the device was manufactured. With Frohman's device, data could be stored easily using simple equipment.

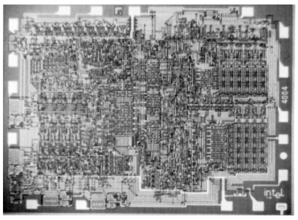
Frohman also made the fortunate discovery that the charge stored on the floating gate could be dissipated by illuminating the transistor with ultra-violet radiation. Thus, if the chip were mounted in an encapsulation with a transparent window, the stored data could be erased and re-programmed at will. The device was given the acronym EPROM (Erasable Programmable Read-Only Memory) and found a ready market. As a result of its successful launch, Intel's revenue increased from $9m in 1971 to $66m in 1973.

4.3.3 The microprocessor

Another product for which Intel obtained a development contract was a set of chips for a desk-top calculator to be produced for the Nippon Calculating Machine Corporation. NCM's requirement was to design and manufacture a set of eight logic chips which would be pre-programmed to carry out the basic arithmetical functions for a calculator which they would sell under the name Busicom. However, as Intel already had three different memory circuit projects in progress, it did not have the resources to carry out eight new logic chip designs. Ted Hoff, the ex-Stanford engineer who had invented the DRAM cell therefore devised an alternative solution. He proposed a miniaturised general-purpose computer which could then be programmed to do the arithmetic for the client's desktop calculator. Hoff adapted the concept of a general-purpose computer, with which he was familiar from his use of the Digital Equipment Corporation PDP-8, and applied it to the Busicom specification.

The key difference between a general-purpose computer such as the PDP-8 and the customised logic circuits required by the Busicom specification was that the PDP had a subroutine capability: it could stop in the middle of a series of program steps, go off and carry out another job, and then return where it had left off. Hoff's key perception was that by adding the ability to perform subroutine calculations to the Busicom design, he could perform all the high-level functions that the calculator required. The basic computer could then be stripped down to the point where it could perform only the simplest tasks, and all other operations, such as adding a pair of integers together, could be reduced to combinations of these elements.

A consequence of Intel's limited engineering resources was that, although it had won the development contract for the Busicom chip set, there had been little progress on developing it. Eventually, Federico Faggin, a young Italian engineer working at Fairchild, was hired as project leader and set to work on the detailed design. In collaboration with Stan Mazor, an experienced Intel circuit developer, he accomplished the task in four months. However, by the time Intel had completed the chip set, competition in the Japanese calculator market had increased. NCM therefore demanded a price cut. Intel responded with a request to retain the design rights of the chip set. Bob Noyce agreed to refund $60,000 advance on development costs but, in return, wanted to the freedom to sell to others. NCM agreed, subject to retaining exclusivity for calculators. For Intel, this was a crucial decision which underpinned its future success. **Jackson 1997, p61**

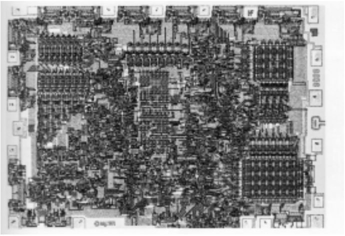


Weber 1981

Fig. 4.2 The 4004, Intel's first microprocessor chip

"A new era in integrated electronics." was the slogan Intel used in November 1971 to introduce the new 4004 microprocessor to the world. **Electronic News, Nov. 1971** However, the bold public face was tempered by private scepticism. Although the computing power of the 4004 matched that of ENIAC, the world's first digital computer, which occupied an entire room and consumed 200 kilowatts of power, the total global market for computers in 1971 was 20,000 units. Even on the optimistic assumption that Intel would capture ten per cent of potential sales, this would mean that the 4004 would generate annual revenues of only $200,000. Success would depend on the creation of new markets, and this was where the ability to program the device would bear fruit.

The 4004 handled data in blocks of four binary units (or bits). Another company, Computer Terminals Corporation, wanted to process data in block of eight bits (or bytes). CTC sponsored the development of an eight-bit processor and this was launched as the 8008 in August 1972.



Weber 1981

Fig. 4.3 Intel's 8008 microprocessor

Although the 8008 raised the prospect of business applications, it was difficult to program. There was no high-level computer language available for the new devices and it was therefore necessary to control them with sequences of binary code – difficult to write and even harder to de-bug. Intel overcame this problem by selling a development system – the Intellec – which facilitated the writing and testing of programs for the new chips. Sales of these development systems generated sales of microprocessors which would, in turn, create sales of peripheral chips to control the flow of data to devices such as printers and keyboards, which worked alongside.

After the 8008, Intel put together a team of Federico Faggin, Stan Mazor and Masotoshi Shima, the design engineer from Busicom who was responsible for the 4004 project, to work on its successor the 8080. Instead of the *p*-channel MOS process, which had been used for the 4K DRAM memory chip, the new device employed *n*-channel field-effect transistors, which were much faster – the 8080 could execute 290,000 operations a second compared with the 60,000 of the 4004. Whereas the 8008 required twenty support chips, the 8080 needed only six. Development took a year and the processor was launched on the market in April 1974 at a price of $360. The chip was an immediate success and repaid the 8080's development costs in five months. [Manners 1996b]

4.4 Covert inventions

The semiconductor industry has always been beset by problems of manufacturing yield. Particularly in the early stages of the development of a new device, the number which reach the desired specification is only a very small percentage of those actually made. Intel started to make insulated-gate field-effect transistor integrated circuits using a revolutionary silicon gate technology which had been pioneered at Fairchild. Very few of the devices tested at the end of the production process actually functioned. However, by meticulous testing and visual examination, Gordon Moore identified the cause of the failures as the thermal cycling during successive stages of the manufacturing processes. The narrow strips of polycrystalline silicon fractured at the sharp corners left where the surface oxide layer had been etched away. Repeated expansion and contraction as the wafer heated and cooled down caused a stress in the material.

Moore proposed a simple solution – dope the oxide with impurities which would have the effect of lowering the melting point of the silica. This would cause it to flow and eliminate the sharp edges which were the cause of the failure. The idea worked. the solution was patented, but secrecy was maintained for as long as possible, giving Intel a competitive advantage over its rivals who were also using the silicon gate process. **Jackson 1997, p27**

In production, the EPROM proved initially to be extremely sensitive to variations in processing techniques, but Intel discovered serendipitously that, if the chips were pre-conditioned by the application of large negative voltage, their characteristics became much more uniform, with a resultant increase in production yields. Intel guarded this secret closely, whilst its competitors struggled to produce viable numbers of good devices. In consequence, Intel was able to charge a high price and generate large profits.

4.5 Legacy systems

After launching the 8080 microprocessor, Intel set to work on its successor. Designated the 8800, this was to be an all-singing, all-dancing chip with advanced architecture. It needed to be, because Intel's principal competitors, Motorola and Zilog, a breakaway group led by Federico Faggin, had launched 8-bit microprocessors, the 6800 and the Z80, which performed better than the 8080, and they were known to be working on 16-bit follow-ups.

The 8800 was to have advanced features. **Jackson 1997, p149** It would have self-checking hardware and be fault tolerant. It would handle true multitasking and variable-length instructions, recognise different data types and utilise the 'object-oriented', features which were to be found only on main-frame computers. The chip would be four times the size of the 8080, the biggest chip Intel had ever built. Unfortunately, an internal audit of its development revealed that there were flaws in the design and, by the time it would be ready to market, it would be too late. Unless Intel took immediate action, the new Motorola and Zilog chips would sweep the board.

Intel instituted a crash programme to develop a stop-gap chip, the 8086. A software engineer was put in charge and he took the decision that the properties of the new processor should be a super-set of those of the 8080. In other words, software written for the 8080 would run on the 8086, albeit much faster. This design philosophy became part of the company culture and was to have profound implications for the future of Intel. Each successive processor was designed to run the software of its father and grandfather. This ensured that there was always a strong user base, whilst the software writers could upgrade their programs with each new launch, taking advantage of the enhanced capabilities of the new chip. What happened subsequently proved to be a matter of luck, but it, at least, ensured that Intel had a seat at the 16-bit table.

4.6 The personal computer

One entrepreneur who viewed the microprocessor as an opportunity was Ed Roberts, who ran a small calculator company, MITS. He designed a simple computer around the 8080 and advertised kits for sale by mail order, the initial advertisement appearing in the *Popular Electronics* magazine for January 1975. Amongst his first customers were two teenagers, Bill Gates and Paul Allen, who wrote interpreter software which permitted the computer to be programmed in the Basic computer language.

The MITS Altair was the start of the personal computer revolution, although, in the early days, it remained the preserve of the enthusiast. One group of these so-called nerds, was the Homebrew Computer Club in San Francisco. A member of this group, Stephen Wozniak, designed a computer based on the Mostek 6502 processor. He named it the Apple I. The processor was a chance choice – it happened to be what the local computer shop had in stock.

Wozniak’s friend, Steve Jobs, recognised that there were potentially large numbers of enthusiasts who would like to program computers, but lacked the electronic skills to construct them from components. He persuaded Wozniak to refine his design and, together, they sought finance to put the computer into production. [Manners 1995, p29] Under the guidance of Mike Markkula, a venture capitalist, they launched the Apple II, which made $700,000 worth of sales that year. The following year, sales were $7 million, and the year after $48 million. In 1980, sales doubled again and the Apple company went public, giving Jobs and Wozniak $100 million each.

The reason for this success was VisiCalc, a spreadsheet program written by Dan Bricklin, a lecturer at Harvard Business School. [Cringely 1996, p62] The “What-if?” calculations it could perform made it an essential tool for the businessman, whilst the low price of the Apple II meant that would-be users could purchase it from their petty cash budgets without involving corporate computer departments, which were firmly wedded to mainframe computing. Many early PCs were smuggled into companies in this way under the guise of desk calculators.

The success of the Apple II signalled an explosion in personal computing. Other machines of the time were the Tandy TRS-80, the Commodore Pet and the Sinclair ZX80, which all helped to bring computing to the masses.

Even Big Blue finally recognised the threat to its dominance of the computer market. In July 1980, it set up a team under Don Estridge, with the objective of producing a personal computer within a year. Because of its late entry into this market, IBM abandoned its customary practice of sourcing all of the major components in-house.

The microprocessor industry was on the threshold of the transition from 8-bit to 16-bit architecture. For this reason, IBM chose not to build its PC round the 8080, or its development, the Z80, produced by Zilog. At this stage of the industry cycle, 16-bit peripheral chips were not yet in production, so the IBM machine was based on the Intel 8088 microprocessor. This had 16-bit internal architecture, but an 8-bit external data bus, so it could use the peripheral chips which were available for the 8080. When the 16-bit were eventually released, IBM was in a position to upgrade its design to use a full 16-bit processor with minimal changes.

Another consequence of the decision to build a machine from standard components was that IBM approached Digital Research (DR) for operating system software and Microsoft for a Basic interpreter. When the envoys from IBM arrived at DR, they were met by Dorothy Kildall, wife of the company's principal and by the company lawyer. Gary Kildall, who had designed the industry-standard CP/M operating system, preferred to go flying. His delegates stumbled over the IBM non-disclosure agreement and the IBM representatives left empty-handed. They then approached Bill Gates, who, although he had no operating system software, did not need any second bidding. He borrowed $50 thousand and purchased the rights to QDOS (the Quick and Dirty Operating System) from a local company, Seattle Computer Products.

Although IBM constructed its computer from standard components, it thought that it would be able to preserve its proprietary position because the internal control software, the basic input/output system (BIOS) was designed by its own engineers and would therefore be protected by copyright. However, third party software houses, using "clean room" techniques, quickly cloned the BIOS and produced machines which emulated the IBM PC. Without IBM's overheads, they were able to undercut Big Blue's selling price and make inroads into the market which had been created by the aura of IBM's trade mark and the technique of fear, uncertainty and doubt (FUD) which its sales force used to prevent corporate data processing departments defecting to competitors. (It was always considered to be safe to buy IBM because everyone else did. If they were wrong, then everybody was wrong and blame was taken collectively. "Nobody ever got fired for buying IBM.")

4.7 Funding

Producing chips at the volume required by IBM placed a great strain on Intel's resources. To help them over this difficult period, cash-rich IBM took a ten per cent equity stake in the company. [Heller 1994, p126] During the ensuing few years, Intel needed further help to cope with the huge development and capital costs engendered by their rapid growth resulting from the new venture. In response, IBM gradually increased its stake to 20 per cent. Intel had posted a loss for five consecutive quarters before IBM's cash injection. Nevertheless, it managed to maintain an arms'-length business relationship. IBM never took more than 20 per cent of Intel's output and the proportion was down to 15 per cent by 1986. This was due to the fact that there was no restriction on the supply of chips to IBM's competitors – a consequence of IBM's fear of anti-trust action. At this stage, Intel was extremely successful, taking 80 per cent of the world's fastest-growing electronics market. IBM's stake was eventually reduced and, finally, sold completely. However, the IBM cash injection enabled Intel to survive a critical period, particularly in 1985 when it was forced to lay off a third of its staff. By 1992, the company was worth $13 billion, six-and-a-half-times its value a decade earlier. Despite heavy spending on R&D ($800 million in 1992) and capital investment ($1.2 billion), Intel still had a year-end cash balance of $2.3 billion. Its sales per employee ($197,000) exceeded IBM's by $9,000 and its R&D spend, as a percentage of revenue, was 16.7 per cent against 10.2 per cent.

4.8 Second sourcing

Second sourcing was a concept derived from military procurement. When Robert McNamara was appointed Secretary of Defense by President Kennedy, he discovered that a major expense was due to the fact that many parts came from a single supplier. He imposed a rule that, wherever possible, there should be a second source of supply. Since, in the early days, government purchases were the main outlet of the semiconductor manufacturers, this became part of the culture of the industry.

The status of second source could be attained either by signing an agreement with the original manufacturer and making a down-payment followed by royalties on sales, or by reverse-engineering the product and setting up in competition. The first method involved the transfer of know-how and conferred credibility with customers. The second was less costly, but was fraught with the risk of being sued for infringement of patents or copyright. In the early days, however, intellectual property rights in the semiconductor industry were either ignored or neutralised by cross-licensing agreements. Second-sourcing was tolerated because customers needed the comfort it provided and the because manufacturers lacked the financial and technological muscle to maintain a monopoly position.

Intel's first experience of these arrangements was fortunate. When it introduced the first 1k-bit DRAM, customers in the computer industry demanded a second source before placing orders. Intel appointed a Canadian manufacturer, Microsystems International Limited. MIL made an initial payment of nearly $1m and followed this up with a stream of royalties, tiding Intel over a difficult financial period during an economic recession. After a while, however, MIL over-stepped itself by introducing process changes in an attempt to increase its production volumes. As often happens in such cases, yields plummeted and orders could not be fulfilled. Intel was able to step into the breach and supply product, making large profits as a result.

Some nine months after Noyce and Moore quit Fairchild, another of its employees left to form his own company. The employee was Jerry Sanders and the company was Advanced Micro Devices (AMD). By the time this start-up had emerged from the drawing board, the financial climate in the industry had changed and it was no longer considered possible to launch a broadly-based semiconductor company. **Jackson 1997, p76** Sanders therefore determined that second-sourcing would be the route he would follow. For this purpose, he hired Sven Simonsen, a Danish emigré who had presided over the design of a range of, what was by then, mature integrated circuits at Fairchild. Simonsen was able to re-create the products without recourse to Fairchild's proprietary intellectual property rights. A leaked memorandum revealed that Fairchild took the threat seriously and AMD used this to promote sales of its chips.

Shortly after, AMD received a lucky break when it was offered and accepted an opportunity to second source a Texas Instruments' chip to be supplied to Westinghouse for a military contract. This had a double benefit because, as well as generating much-needed revenue, it also created large amounts of goodwill for future contracts.

AMD chose the reverse-engineering route to second sourcing, which left the company vulnerable to attacks based on intellectual property rights. **Jackson 1997, p162** One of the products they had imitated was Intel's EPROM. Intel was following its own agenda and, although it did not institute proceedings immediately, in due course, it commenced an action against AMD, alleging infringement of its patents.

Intel had accumulated a substantial war chest from its profits on the EPROM and DRAM, so it used these to flex its muscles. It wanted compensation for AMD's use of its EPROM patents; it wanted the right to second-source AMD's floating-point co-processor which speeded up mathematical calculations and it wanted to improve its credibility in the microprocessor market by having AMD as a viable second source.

Sanders was an astute negotiator and demanded concessions before he would agree to a deal. Intel offered rights to microcode – software embedded in the structure of its microprocessor, which made operation more efficient. Agreement was reached in 1982, and a ten-year contract signed.

> - Assure AMD they are our primary source through regular management contact and formal meetings.
> - Take no more AMD products under the current agreement.
>
> Bullet points from Intel internal memorandum, 1984

> 'Keep AMD in the Intel camp.'
>
> 'Key point we are in no hurry. We don't need a 386 second source, especially since everyone assumes AMD will be one.'
>
> Intel internal memorandum, 1985

> 'Maintain a second source, business as usual posture in the market place ... Our strategy is to keep talking ... We do not want them [AMD] to get to Hitachi or NEC, and should not stimulate them to do so.'
>
> Intel internal memorandum, 1986

Almost as soon as it was signed, the deal started to go sour. Sanders made public statements, crowing about AMD's successes and questioning Intel's competence. Andy Grove, Intel's general manager was put out by these overt attacks and vowed to gain his revenge. **Jackson 1997, p230**

Two years after the original agreement was signed, the two parties re-negotiated its terms. AMD wanted rights to Intel's new processor chips, the 80186 and the 80286, and agreed to pay a fixed price rather than a percentage royalty for the right to make them. During the preliminary discussions, Intel hinted that the rate would be reduced, if it decided to second-source two of AMD's peripheral integrated circuits, although, in fact, it had no intention of pursuing this course. When the new agreement was signed, Intel made its true intentions known. This decision was to have disastrous consequences for AMD, since the fixed royalty rate would consume an ever greater proportion of its gross profit when selling prices fell as the market matured. The effect would be that AMD would be starved of cash flow.

AMD eventually embarked on a course of litigation, in an attempt to gain what it thought it was entitled to. From this it was to learn two lessons – that the only ones who get rich through the process of law are the lawyers and that fighting legal battles ties up valuable resources which should be deployed on the mainstream task of generating profits for the company.

Indeed, this was just one of a number of occasions on which Intel entered into proceedings with the sole objective of delaying a competitor's entry into a market. An initial monopoly permits the market leader to set its own pricing policy which may be utilised to control its competitor's cash flow. By charging a high price at the outset and then reducing it as competitors appear, it can reduce their gross profits because they are at an earlier stage on the learning curve.

4.9 Competition

4.9.1 Rival microprocessors

Intel followed a programme of developing ever more complex microprocessors. With each successive launch, it consolidated its position and increased its dominance of the market. Its customers were trapped on a treadmill and were constantly seeking ways to escape from Intel's clutches. One conceivable way would be to buy processors from one of Intel's competitors, such as Motorola or Zilog. However, these had a different architecture and would not run software designed for Intel chips without major changes. Furthermore, there was no critical mass of customers for machines based on a different form of construction. A paradigm shift of this nature was not, therefore, feasible.

There was an alternative possibility. IBM had invented the concept of a Reduced Instruction Set Computer (RISC). **Cullis 1986** The concept on which it was based was that the complex operations of a state-of-the-art processor could be simulated, under software control, by a sequence of simple operations. If these operations were performed extremely quickly, then the RISC processor would out-perform the Complex Instruction Set Computer (CISC). RISC-based software could thus emulate CISC-based software.

That was the theory, but it failed for a number of reasons. Firstly, running the compact RISC code involved far more data flow between the processor kernel and external memory. This would inevitably be less efficient and slower than the optimised internal communication of the CISC processor, the design of which could be optimised on the basis of Pareto criteria. Secondly, to implement the approach would require great commercial courage. Initially, at least, the economies of scale resulting from following *de facto* industry standards would be lost. Margins were such that an original equipment manufacturer (OEM) who adopted this approach would almost certainly fail unless he were supported by cross-subsidies or government funding. Nevertheless, the RISC processor remains an ever-present spectre to haunt Intel by threatening its dominance.

The Unix operating system was devised at Bell Labs as a universal software interface for a variety of different computers. In 1988, Microsoft adopted a similar approach and commenced the development of an operating system with a graphical user interface which would, likewise, run on any computer. **Jackson 1997, p304** In 1991, they formed a consortium of twenty-one companies, including both computer and RISC processor manufacturers, to develop the concept further. The new operating system, Windows NT, was, however, profligate in its use of computing resources, so mainstream manufacturers like Dell and Compaq did not desert the Intel camp, but launched computers based on the Pentium processor, which offered a less demanding solution. In 1991, Intel sold 20.4 million processor chips; the combined efforts of the RISC chip makers achieved only 308,000. **Heller 1994, p124**

The main alternative to microcomputers based on the Intel processor family was the Apple Macintosh, which was designed around the Motorola 68000 range of processors. In an attempt to replace Intel's monopoly with one of their own, IBM, Motorola and Apple formed an alliance to build computers, which would run both PC and Mac software, based on a new chip, developed from the 68000 and designated the PowerPC. In prospect, the PowerPC offered a 60 per cent improvement in performance, but, when it reached the marketplace, it was riddled with bugs and only delivered a 15 per cent enhancement. **Jackson 1997, p370** Eventually the consortium disintegrated and the concept foundered.

Another possible non-Intel line of development was the Digital (DEC) Alpha chip which posed a serious threat at the top end of Intel's market. However, this niche was insufficient to sustain a semiconductor business and DEC, after protracted patent litigation with Intel on a number of issues, sold its chip fabrication facilities to Intel as part of an agreed settlement to the action. **Electronic News, 3 Nov 1997**

One manufacturer which did succeed in carving out a viable niche was the small British manufacturer Acorn. The company came into being during the explosive genesis of microcomputer makers which followed the invention of the microprocessor. It survived the early days by servicing the UK educational market with the BBC microcomputer. One of the products of its R&D programme was a RISC processor, originally called the Acorn RISC Machine, but later re-named the Advanced RISC Machine. The processor was a well-rounded design, which evolved from the Mostek 6502 8-bit microprocessor used to power the BBC micro. With its peripheral functions, the design formed the basis of an engine to power a multitude of embedded applications and Acorn's spin-off company capitalised on these in a profitable licensing programme.

4.9.2 Commodification of memory chips

> "Quote 10% below their price; if they requote, go 10% again. Don't quit until you win."
>
> **Hitachi** memo to EPROM distributors

> "Because of severe competition and anticipated cost reductions, Intel and its competitors typically offer products for future delivery at prices below current production costs. If costs do not decline as anticipated, such sales may result in losses."
>
> **Intel** IPO document

The Japanese Government made a political decision to develop the country's national semiconductor industry. Despite previous requirements for a minimum of fifty per cent local ownership, it permitted Texas Instruments to establish a Japanese subsidiary with only one third of the shares owned locally. The rationale behind this relaxation was that it would improve trade relations with America, it would introduce chip-making skills and it would lay the foundations for competition with the American chip industry. **Manners 1995,p 43**

In 1970, MITI (the Ministry for International Trade and Industry) took the next step towards achieving technological parity with the US when it initiated the VLSI programme. This was intended to give Japanese companies the capability of manufacturing very large scale integrated circuits. MITI coerced the industry into investing ¥40bn and backed this with a subsidy of ¥30bn. As a result, in 1983, Hitachi and NEC were manufacturing state-of-the-art 256kbit memory chips.

The Japanese approached the task with determination and thoroughness. Meticulous attention to detail and greater stability of staffing meant that their yields improved at a faster rate than those of US companies. This improvement went straight to the bottom line, with the result that they were able to undercut their competitors, whilst still maintaining profitability. And even when the revenue account went into the red, the fact that semiconductors represented only a small proportion of the sales of the Japanese companies, enabled them to cross-subsidise their operations to buy market share.

The global semiconductor industry was subject to periodic recessions during which the free-market-economy US companies gradually re-trenched, whilst the subsidised Japanese companies stood their ground. Eventually, only the Japanese were left.

During the 1980s, the Korean and Taiwanese governments also took the political decision that they would subsidise the creation of domestic semiconductor industries. They created a huge manufacturing capacity which exacerbated the cyclic gluts in the commodity semiconductor chip markets.

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4.9.3 The balance of reward and risk – quit while you are ahead

> “It was an emotional decision. We had been the first to introduce the product and build the business. Even as we were losing market share hand over fist, we clung to the idea that we'd come back. DRAM was taking a third of Intel's R&D dollars and contributing only 5% of its revenues. Pulling out freed resources to go into microprocessors. It was one of the toughest and the best decisions we ever made.”
>
> **Andy Grove**

Shortly after Intel’s successful launch of the EPROM, the digital watch loomed over the horizon. It seemed like an excellent opportunity to diversify, so Noyce and Moore persuaded the Intel board to purchase Microma, a start-up digital watch company. It was projected that, within seven years, digital watches would account for one third of the watch industry’s turnover. This projection was based on two premises – that liquid crystal displays would by then have replaced light-emitting diodes and that the price of an LCD-based watch would have fallen to $30.

In fact the selling price had fallen to $9.95 within a couple of years and Microma did not possess the skills to compete successfully in this commodity market. Intel decided to cut its losses and dispose of the watch company. For years after, Gordon Moore wore one of the watches, telling anyone who asked, that it cost $15m.

For Intel, DRAM sales grew from $9m in 1974 to $15m in 1975, $23m in 1976 and $38m in 1974. They peaked at $41m in 1978 and, under the influence of Japanese competition, fell back to $32m in 1979. This signalled the onset of a decline in market share of commodity products in which it enjoyed no unique competitive advantage. In 1982, it ceased to manufacture SRAMs and, in 1985, it abandoned DRAMs. Although it was still market leader, it quit the EPROM market in 1992, preferring to allocate the resources to the manufacture of FLASH memory, which performed the same function, but was electrically erasable, as this would, in due course, supersede the EPROM.

Intel, however, remained firmly in the microprocessor market, for which, in 1994, it built three new factories at a cost of $1bn each. This was an area over which it had exclusive control by virtue of customer inertia and response-time delay, as well as by intellectual property rights.

4.10 Intellectual property rights

4.10.1 Mask topography protection

A major proportion of the design effort for a new integrated circuit goes into the development of the device topography and one of the key elements in second sourcing agreements is the supply of masks for the photolithographic processing of the silicon wafers. For the 8086, Intel had provided copies of the masks to twelve different companies.

For an unofficial second source, it was a relatively simple matter to make a copy of the layout and thereby avoid considerable trouble and expense. It could be argued that the creation of the masks was an artistic work ad therefore enjoyed copyright protection. However, since the design was purely functional, the outcome of litigation based on this premise could not be regarded as certain. Andy Grove, therefore, felt that there should be specific protection and commenced lobbying for new legislation to be passed. In 1980, a group of congressmen was taken on a tour of the company's computer-aided design facilities, to show them how much effort was involved in designing masks and how vulnerable American industry was to foreign copying. Intel's lawyer even provided an initial draft bill, but this did not receive the wholehearted support of other companies in the industry. Eventually, the new *sui generis* protection reached the statute book in 1984 as the Semiconductor Chip Protection Act.

Having created domestic legislation, the USA then prevailed on its trading partners to follow suit, **US Off Gaz 13 Nov 1984, p30** with the result that a framework of laws against integrated circuit piracy was established in all important manufacturing territories.

4.10.2 Microcode

Another development introduced with the 8086 was microcode, a group of small programs built permanently into the architecture of the processor. Selecting appropriate sequences of these routines greatly enhanced the overall speed when the processor was executing more complex operations. Although it had already been established that computer software enjoyed copyright protection, it was a moot point whether this extended to embedded microcode.

Nippon Electric (NEC) took a licence from Intel to make 8086 and 8088 processors. It then developed its own versions, the V20, V30 and V40. In order to retain control of its architecture, Intel sued NEC for infringement of copyright in its microcode. NEC counter-argued that the microcode in its chips had been written by its own programmers.

During the course of the litigation, NEC commissioned a further, clean-room version of the design. In evidence, it submitted that parts of the clean-room microcode bore a greater resemblance to the Intel microcode than that which was alleged to be copied. Similarities, it was argued, were due to identities of design constraints rather than to copying.

Intel eventually lost the case on technical grounds, because it had failed to ensure that appropriate copyright notices were affixed to all of its licensees' products. However, an ancillary outcome was a decision that microcode enjoyed copyright protection, a precedent which would give Intel an additional hold over its licensees and ensured that would-be cloners would have to go to the expense of using clean room techniques.

4.10.3 Patents

Fig. 4.4

Copyright subsists from the moment of the committal of a literary work to a reproducible medium. There are no initial costs and no renewal fees. Patents, on the other hand, carry a significant cost penalty. To protect a single invention may cost £100,000 to £200,000 and this will increase by at least an order of magnitude if litigation is undertaken. A portfolio of patents may be used defensively as currency in cross-licensing agreements or offensively to put up the cost of market entry to competitors. For the first twenty years of its existence, Intel paid scant attention to patents. [Cullis 2004, Appendix 9] In the 1990s, however, there was a major change of policy and the number of filings increased seven-fold to around 350 per annum.

4.10.4 "Intel Inside"

Following its strategy of making successive microprocessors upwards compatible with their predecessors, Intel moved sequentially from the 8086 to the 80186 and 80286. With the 80386 it was beginning to acquire substantial market power and to consider strategies to eliminate competition. The 80486 marked a sea change with an absence of second-sourcing agreements. Manufacturers such as AMD and Cyrix, however, continued to produce clones of the Intel processors by adopting clean room techniques and prepared to launch an 80586. At this stage, in order to reduce the effectiveness of their marketing operations, Intel changed its own tactics. It was no longer necessary to emphasise the origins of a processor – the ability to work with historic code had become part of the received design philosophy – so promotion could concentrate on reinforcing exclusivity. The next generation was named the Pentium processor and a huge advertising campaign based on the slogan "Intel inside" was launched to coerce the end user into demanding a specific brand rather than just particular functionality for the processor chip in his new computer.

Intel agreed to share the cost of computer companies' own advertisements provided they included the 'Intel Inside' logo with appropriate prominence. Each customer was assigned a marketing development fund equivalent to three per cent of its microprocessors purchasing budget. Intel would then use this fund to pay up to half the cost of the advertisements. In this way, Intel ensured that it received maximum exposure to the audiences its customers considered to be important.

In 1992, the first full year of the campaign, Intel's sales rose 63% and its brand was ranked by marketing analysts as the third most valuable name after Coca-Cola and Marlboro. The "Intel Inside" logo became so popular that some PC makers were prepared to use it even without a contribution from Intel.

4.10.5 Use of the legal process

In common with a number of other companies in the semiconductor industry, Intel refused to take a licence from AT&T under the Bell Labs' portfolio of semiconductor patents. Eventually AT&T issued a writ and Intel's counsel, Roger Borovoy, elected to fight the case himself rather than retain external lawyers. During the pre-trial discovery procedures – when the litigants were given access to the other parties records – he found out that AT&T had concealed earlier research when filing a key patent application, [US Pat 2802760] in order to obtain a later filing date and thereby circumvent the provisions of an anti-trust consent decree requiring it to grant free licences on all patents up to a certain date. Under the so-called "clean-hands" doctrine, this would have invalidated the later patent. Borovoy used this newly-acquired information to negotiate a very favourable settlement with AT&T. [Jackson 1997, p119]

The key to Intel's success was the financial power it gained from being ahead of its competitors on the learning curve. A measure of this was that, in 1984, the company was selling '286 processors, which cost $34 to make, for $250, and was selling samples of the next-generation '386 processors, which cost $141 to make, for $900. At this time, the average price of a standard 8-bit processor was only $4.06.

This was the context for the battle between AMD and Intel over the right to second-source the 80386. Intel created delay by refusing AMD's request for arbitration of their 1982 technology-sharing agreement, forcing AMD to go through the full legal process to get an arbitrator appointed. They then filibustered to such an extent that he was not in a position to give his conclusions until 1990.

The arbitrator criticised AMD for being ingenuous about its relationship with Intel and for failing to meet its obligations, by delivering low-quality chips to Intel. He accused Intel of calculated bad faith in frustrating the working of the agreement, and by holding out the carrot of a ’386 licence even though it had already made the decision not to grant one. He granted AMD a ‘permanent, nonexclusive and royalty-free licence’ to the 386. Intel did not accept this decision and went to the courts for a declaration that the arbitrator’s decision was *ultra vires* and pursued the case all the way to the State Supreme Court before the arbitrator’s decision was finally upheld in 1994. The cost of these machinations were small in comparison with the rewords of the longer period of exclusivity in the market place.

The strategy was repeated in 1996 when the two companies signed a new patent licence agreement. The new agreement, announced only five days after the old one had expired, ran for just five years compared with the previous agreement’s twenty. The agreement had two significant exclusions **Jackson 1997, p382** – AMD was forbidden to use Intel’s microcode beyond the 486 generation, a not unreasonable exclusion, but, more importantly, it was not permitted to design its processors after the Pentium generation so that they were plug-compatible with Intel’s, a requirement that might be described as waving a red rag before the anti-trust bull.

The reason for the second stipulation was that Intel was attempting to change its sales strategy. Instead of supplying OEMs with just the chips, it was proposing to mount the processor as a subassembly module to increase its profitability. It wanted to exclude AMD from this opportunity.

Amongst other things, the new agreement licensed AMD to use a new development, a range of processor operations for handling graphic images and sound, known as multi-media extensions. However, just before AMD was about to launch its new K6 rival to Intel’s Pentium Pro chip, Intel filed a complaint in the Delaware Federal Court, claiming that MMX was an Intel trade mark, notwithstanding the fact that it was universally regarded as an acronym. Intel’s complaint included six counts: false designation of origin, false advertising, trademark infringement, trademark dilution, deceptive trade practices, common law trademark infringement and unfair competition. It argued that, as it had spent heavily on promoting MMX, AMD should not be allowed to free-ride on this investment.

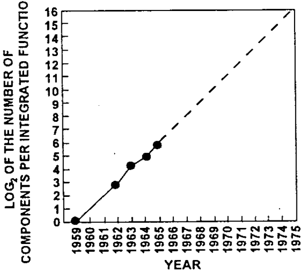
Intel took AMD right up to the wire, but eventually agreed to settle the case. In return for AMD acknowledging the validity of Intel’s trademark rights to MMX, AMD would be granted the right to use the trademark free of charge.

4.11 Moore's Law

> "The complexity for minimum component costs has increased at a rate of roughly a factor of two per year. Certainly over the short term this rate can be expected to continue, if not to increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain constant for at least 10 years."
>
> **Gordon E. Moore**
> 1965

> "There is no room left to squeeze anything out by being clever. Going forward from here we have to depend on the two size factors – bigger dice and finer dimensions."
>
> **Gordon E. Moore**
> 1975

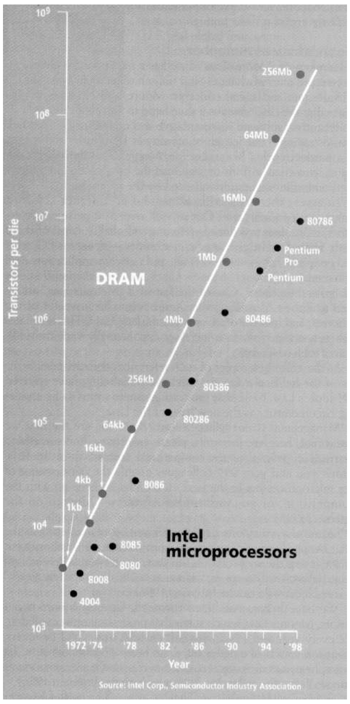
> "By making things smaller, everything gets better simultaneously. There is little need for trade-offs. The speed of our products goes up, the power consumption goes down, system reliability, as we put more of the system on a chip, improves by leaps and bounds, but especially the cost of doing things electronically drops as a result of the technology.
>
> More than anything, once something like this gets established, it becomes more or less a self-fulfilling prophecy. The Semiconductor Industry Association puts out a technology roadmap, which continues this generation [turnover] every three years. Everyone in the industry recognizes that if you don't stay on essentially that curve they will fall behind. So it sort of drives itself."
>
> **Gordon E. Moore**
> 1995



Moore 1965

Fig 4.5 Gordon Moore's original extrapolation

In a landmark paper **Moore 1965** to celebrate the thirty-fifth anniversary of *Electronics* magazine, Gordon Moore, then R&D Director of Fairchild Semiconductor, had been invited to speculate on possible developments in the semiconductor industry during the coming decade. Moore predicted that, by 1975, silicon integrated circuits would contain 65,000 components on a chip 6mm square. He based his forecast on an extrapolation of empirical data from three data points from his work at Fairchild. His starting point was the production of the first planar transistor in 1959. The next point was a scatter of the first few integrated circuits of the early 1960s, including the production in 1964 of one with 32 components. His last was his own knowledge that a chip due to be launched later in 1965 would contain 64 components. **Schaller 1997**



Source: Intel Corp., Semiconductor Industry Association

Schaller 1997

Fig. 4.6 Intel microprocessors and DRAM memory chips as an example of Moore's Law

Moore read a further paper on the subject at the 1975 IEEE International Electron Devices Meeting. His explanation for his "law" was the ability to use large die sizes without reduction in yields. This was due to the use of projection techniques rather that contact printing in photolithographic processes and to the reduction in size of topographical features such as line widths. These attributes accounted for two-thirds of the previous decade's improvement. The remainder was due to what Moore called "circuit and device cleverness", such as the development of ion implantation rather than chemical deposition for introduction of dopants. He concluded that there was no prospect of further gains from this latter paradigm and, although he prognosticated further gains in packing density, he postulated that the doubling would henceforth take place only every eighteen months.

In 1995, Moore was able to produce retrospective data for three decades. He plotted component densities for two types of device – microprocessors and memory chips. Both exhibited a log-linear relationship, but memories – a simpler component – achieved consistently higher densities. Die sizes had continued to increase, whilst line widths became smaller, at exponential rates consistent with his 1975 analysis (Fig. 4.6).

For the semiconductor industry, Moore's Law has become almost a self-fulfilling prophecy, creating synergies whilst, at the same time, establishing milestones which must be passed to keep pace with general progress.

The growing power of hardware, manifest in Moore's Law, has permitted relaxation in the constraints imposed by the labour-intensive nature of writing software. Tiny Basic, the language written by Bill Gates and Paul Allen, occupied two kilobytes of memory. In 1975, Microsoft's Basic language had 4000 lines and, two decades later, roughly half a million. The first version of Microsoft Word occupied 27,000 lines. By 1997, this had expanded to about two million.

Nathan Myhrvold, chief technology officer of Microsoft wrote

> "So we have increased the size and complexity of software even faster than Moore's Law. In fact, this is why there is a market for faster processors – software people have always consumed new capability as fast or faster than the chip people could make it available."
> "We like what we get, we want more, which spurs people to create more. If there is a lack of positive feedback, the whole things just slows down."

Reduction in the marginal cost of hardware has generated an explosive expansion in the volume of system software.

Although, under the current paradigm, Moore's Law will continue to serve as a predictor of the growth of the semiconductor industry, other factors will increasingly come into play. At present Keynesian influences drive suppliers along the path of technological development. Eventually, physical parameters, such as the magnitude of the charge on a single electron and optical limits on the ability of lithography to produce even smaller feature sizes, will provide an endpoint to further increases in packing density.

As time passes, economic constraints will exert greater influence. Moore observed that capital requirements also rise exponentially. The cost of a new fabrication plant went from US $14 million in 1966 to $1500 million in 1995. In 1998, first $3 billion fabrication plant is being constructed. If the exponential trend in fabrication costs continues, by 2005 the cost of a single plant will be more than $10 billion – more than half of Intel's 1997 net worth.

This increasing cost of market entry for each new generation has led to new funding arrangements. IBM, Siemens, and Toshiba formed a multinational consortium for the development of advanced DRAMs. In Korea and Taiwan, there are state-organised consortia. Global alliances have become the new market model for manufacture of semiconductors.

Marginal profit represents another economic threat to Moore's Law. Dan Hutcheson, president of VLSI Research Inc., San Jose, Calif., reached that conclusion in 1995:

> "The price per transistor will bottom out sometime between 2003 and 2005. From that point on, there will be no economic point in making transistors smaller. So Moore's Law ends in seven years."

4.12 Conclusion

The development of very large scale integrated (VLSI) circuits was the inevitable consequence of Jean Hoerni's invention of the planar process and Bob Noyce's development of etched metallic film interconnections. As with many major breakthroughs, the basic ideas were also identified by others – notably Frosch and Derick at Bell Labs – but the successful company was the one which pushed them through to a logical conclusion. The received wisdom was to etch away the oxide diffusion mask. Fairchild left it on as a surface passivating layer.

There *were* changes in the fabrication technologies **Cullis 2004, Appendix 11** during the Schumpeter B-phase. Processes such as ion implantation and molecular beam epitaxy provided greater precision in the placing of impurities in the semiconductor wafers, but they achieved, in essence, the same end result as the less-refined, early processes of thermal diffusion and chemical vapour deposition. The principal economic consequences resulted from new applications of these fabrication technologies, notably, to the memory cell and the microprocessor.

The personal computer was an obvious application of the microprocessor, but it was of major importance because it permitted bipedal advance. New software could be developed on old processors and migrated easily when a new processor was introduced, giving the innovation an immediate user base. Bill Gates succeeded because he was in the right place at the right time – which was *not* flying his aeroplane over San Francisco bay.

Intel was founded by entrepreneurial characters who were not content to work for others. It set out to provide a product which the market needed (semiconductor memory). As with the incandescent lamp and the transistor, the decision to go for a latent market created by an alternative, but flawed, technology made success of the memory chip inevitable, provided the product could be made satisfactorily. Backing three horses to be sure of being first to the winning post was the successful strategy adopted by Intel.

Its first leap forward was the DRAM, the result of an enlightened trade-off – the addition of a cheap power supply gave an order of magnitude performance improvement. The EPROM, on the other hand, was the serendipitous recognition of the opportunities offered by a physical effect. The opportunity was, however, a manifestation of Pasteur's prepared mind syndrome, since both the initial discovery and the later development were identified as a result of painstaking investigation. The microprocessor, like the integrated circuit, was a logical extrapolation of a proven product (the DEC PDP-8 computer) – make it smaller, make it in one piece. The skill lay in reducing the idea to practice and this was driven by the need to make best use of scarce resources.

The success of Intel was founded on the lucky choice of the 8088 processor to power the first IBM PC. However, this was an example of the successful making their own good luck. The reason that the 8088 was chosen was that the necessary peripheral chips were readily available and the next-generation processor(the 8086) was already in prospect.

By definition, start-up companies are starved of resources. Intel lacked a cash cow which was sufficiently fruitful to meet the demands of the expansion engendered by the runaway success of the IBM PC. Fortunately IBM was in a position to play fairy godmother by taking an equity stake at the appropriate time. Fortunately, also, IBM was so frightened by the prospect of anti-trust proceedings that it failed to exact the full price of exclusivity which it could reasonably have demanded.

Recognition of when to quit is an important component in achieving commercial maturity – Intel left the memory chip market when it became unprofitable and very quickly abandoned a foray into digital watches. Another reason that Intel succeeded was because it made full use of the legal process. Like the politicians who rejected Edison's vote counter, it recognised the importance of delay, which, for Intel, amplified the effects of response time monopoly. Intel was not afraid to hit below the belt if that would achieve an appropriate result. The name of the game was domination and legal filibustering was one of the tools available. Intellectual property monopolies were another. *Sui generis* rights could be created by exerting the right political influence. Market power coupled with the characteristics of the learning curve could be used to control the cash flow of competitors and maintain a quasi-stable monopoly indefinitely.

However, either timidity engendered by lack of confidence or possibly naïvety regarding intellectual property matters in a start-up organisation resulted in failure to establish a dominant patent position with memory circuit chips. The consequence was that competition increased, these products became commodities and the markets ceased to yield viable returns. With the microprocessor, Intel failed to establish the absolute monopoly that patents would have provided. In that case, it succeeded because it won a captive market which would be created and supported by

IBM. George Westinghouse laid the foundations for Tesla's ac machines in an analogous manner.

A positive management decision to go for a market- rather than a production-led approach resulted in the creation of a legacy-system evolutionary model, which maintained Intel's initial hold and locked customers into its products. This tactic, which was embraced as a result of failure of a proposed ground-breaking product to meet a critical development timetable, was supplemented by a willingness to exploit the legal process to enhance response-time delays, thereby emasculating competitors by controlling their cash flow. Not until the industry was well established did Intel turn to the use of patents and trade marks to reinforce its control of the market. It did, however, exhibit a prudent and opportunistic political attitude. It lobbied effectively to obtain enactment of *sui generis* intellectual property rights (semiconductor mask protection legislation) and, while its predatory techniques in the market place were not dissimilar to those of Microsoft, it reacted in a conciliatory manner and compromised with the authorities on anti-trust matters, whereas Microsoft was more confrontational and became involved in major litigation with the US Justice Department. It is too early to say whether this difference will have any long-term effect, but it did, in the short term conserve resources and allow Intel's management to concentrate on the primary role of developing the business.

Intel succeeded because of the hare and tortoise syndrome. Success comes not to those who make rapid advance, necessitating a fresh start each time, but to those who make an incremental change and build on an existing foundation – like Newton standing on the shoulders of giants. To some, the decision to make each generation a superset of its predecessor was reactionary, but for Intel it delivered a core of users who could be up and running immediately.

The rise of Intel was largely a matter of luck, albeit supplemented by a responsive and sometimes cynical management whose decisions, on balance, proved to be correct more often than they were wrong.

The case study demonstrated that the path of evolution of the industry was determined by specific events. The progress would clearly have been different without the influence of IBM, or if Intel had used patents to establish a monopoly over memory chips and the microprocessor.

Under the current paradigm, Moore's Law serves as a predictor of the growth of the semiconductor industry, but other factors will increasingly come into play. At present Keynesian influences drive suppliers along the path of technological development. Eventually, physical parameters, such as the magnitude of the charge on a single electron and optical limits on the ability of lithography to produce even smaller feature sizes, will provide an endpoint to further increases in packing density. As time passes, economic constraints will exert greater influence.

The case studies set out in this book have presented an overview of different aspects of the dynamics of innovation. The first and second provided contrasting perspectives of evolution over a relatively large period of time and under changing macroeconomic influences, whilst the third and fourth gave an insight into the differences between the initial and mature-product stages (Schumpeter's A- and B-phases) of a common innovation.