THE CARRIER WAVE

New Information Technology and the geography of innovation, 1846–2003

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The electronic revolution

Electronics represented a product of the third Kondratieff, but (as seen in Ch. 6) a late one: though the basic innovations came in the first decade of that long wave, their mass industrial applications – in radio in the 1920s and 1930s and in radar during the 1940s – coincided with its downswing. It was thus only at the onset of the fourth Kondratieff, during the early 1950s, that the pace of electronic innovation dramatically quickened, starting to create a stream of microelectronic components and systems that became the core of the modern New IT. And this in turn became a key technology of the fourth Kondratieff, as distinctive in its turn as cars and electrical products and pharmaceuticals in the third, Bessemer steel and machine tools in the second.

At last New IT was free of the constraints of crude mechanical systems, which had aborted the birth of Babbage's computer and hindered the early development of many office technologies. Information, stored in huge amounts and processed by increasingly miniaturized systems, progressively became the main agent of economic growth; during the fourth long wave, the main emphasis in the world's advanced industrial economies was moving decisively from the production of goods to the manipulation of information: and there occurred a shift towards the 'convergence of all modes of communication and information technology into one common digital art of transmission, processing, storage, and retrieval, whatever the content, whether it be sound, sight, figures or symbols' (Inose & Pierce 1984, 1).

The transistor: core technology

The invention of the transistor (at Bell Laboratories, Murray Hill, New Jersey on 23 December, 1947) was without doubt one of the technological keys that opened the fourth Kondratieff. The transistor is a device which uses semiconductor materials to perform functions such as amplifying or switching an electrical current. It has many advantages over the thermionic valve on which the electronics industries were based during their first half-century: significant reductions in size and energy consumption, increased reliability and range of applications. Its invention was the work of three physicists at Bell, John Bardeen, Walter Brattain and William Shockley, but it stemmed also from the endeavours of many hundreds of researchers working in many different places on related electronic technologies during and before World War II. Down to 1941, indeed, the UK and perhaps Germany were ahead in the field, but then – with a massive wartime effort in radar detection at MIT and other places – the USA took a clear lead. Yet its discovery in the Bell Laboratories was far from accidental; it was a direct result of the huge state-supported scientific and technical resources dedicated to the work, in what was already the world's largest industrial research organization. But fundamental research in the UK may have lagged behind Bell by only a matter of weeks (Braun & Macdonald 1982).

The first Bell transistor, a germanium point contact transistor, was soon adopted for commercial production by Western Electric, the manufacturing arm of AT&T; but it proved very difficult to manufacture in bulk and suffered from many problems of reliability. Some of these difficulties were overcome in 1951 by Shockley's invention of the junction transistor. But commercial applications and interest in the transistor were rather slow in the early years of the 1950s, in part because of continuing difficulties in standardized mass production techniques. Indeed, process innovations proved almost as important as product innovations in the subsequent history of electronics components technologies (OECD 1968, Braun & Macdonald 1982).

One of the most crucial came in May 1954 when Texas Instruments succeeded in making the silicon transistor; it had the capacity to work at very high temperatures and proved of great interest to the military, whose support provided a major impetus to the development of transistor production in the USA over the following decade (OECD 1968, Braun & Macdonald 1978). A second was the planar process of 1959, which offered many advantages over previous methods for the standardized production of transistors and later more integrated and compact components. It came from Fairchild Semiconductor, a relatively new company started by eight scientists who had previously worked at Shockley's Palo Alto laboratories before starting up with support from Fairchild Camera and Instrument Corporation. By making semiconductors relatively robust and reliable, the planar process did much to set the industry on the growth path it followed for the next quarter-century; from 1959 to 1962 prices fell by 80–90%; between 1957 and 1965 production increased twentyfold by volume (Braun & Macdonald 1982, Dummer 1983).

The second key product innovation was the integrated circuit, which perhaps marks the real step towards the establishment of microelectronics as a major new technology system (Dosi 1984a, 1984b, Perez 1985). It allowed the manufacture of many individual electronic components and functions on a single microchip. It was conceived theoretically as early as 1952 by G.W. Dummer of Britain's Royal Radar Establishment (the RRE) (Freeman *et al.* 1982, Dummer 1983). The first working model was developed under contract to the RRE by the British firm of Plessey in 1957 (OECD 1968); the first patent, a rather crude device, was filed in 1959 by Texas Instruments. It was finally Robert Noyce at Fairchild who demonstrated how these devices could be easily and reliably manufactured using the planar process. The first commercial application of integrated circuits was in hearing aids in 1963 but the military provided the most important early market; by 1970, however, with early production problems resolved and prices lowered, their share was down to one-third (OECD 1968, Braun & Macdonald 1982). As with the transistor, the 1960s saw progressive process innovation, producing increasing numbers of electronic functions on a single microchip, with rapid falls in price per function plus increased reliability and range. The discrete components incorporated in each integrated circuit increased from less than 10 in 1960 to 100 000 in 1980, and the average price of the integrated circuit fell from $50 in 1962 to about $1 in 1971 (Braun & Macdonald 1982).

The third major product innovation was the 'microprogrammable computer on a chip', or microprocessor, developed by an Intel team headed by Ted Hoff in 1971. By the mid-1970s the industry had completely changed its emphasis from the manufacture of discrete integrated circuits to the manufacture of what were in effect small computers; about 40 different microprocessors were being produced in the USA by almost all the major semiconductor manufacturers, with full support systems available. The early 4-bit and 8-bit microprocessors were followed by 16-bit and 32-bit devices in the early 1980s, and the size of the standard dynamic random access memory chips has increased from 1k in the early 1970s to 64k and 256k by the mid-1980s (Braun & Macdonald 1982, OECD 1985).

It was the microprocessor with its capacity to perform 'the full range of logic functions on every kind of information presentable in digital form which is responsible for much of the rapid diffusion of modern electronics into new applications in new areas' (Braun & Macdonald 1982, 112). Aided by the new MOS (metal oxide semiconductor) technology, which became commercially viable only in the early 1970s, an explosion in capacity took place both in microprocessors and in memory, from 5 transistors per chip in 1962 to some 150 000 in 1982; by the 1980s one chip would carry as much information as a middle-range machine of a decade before, and at negligible cost. The main consequence was a further dramatic fall in the time and cost of processing information; the price per bit of dynamic random access memory fell at an average rate of about 35% per year from 1970 and is expected to continue at this rate into the future (Braun & Macdonald 1982, OECD 1985). The direct consequence, as will shortly be described, was that the computer became a cheap mass product.

These advances came almost exclusively from industry, albeit with major support from government and especially from the military, which both paid for R&D and provided much of the early market, above all in the USA; in the mid-1950s defence contracts accounted for one-third of all semiconductor sales, by the late 1950s one-half (OECD 1968, Braun & Macdonald 1982). At first the established valve firms were the main beneficiaries of military R&D contracts, winning 78% in 1959, but even then new firms had 69% of procurement contracts, allowing them to develop new products and thus pass rapidly down the 'learning curve' to high volumes and low costs (Braun & Macdonald 1982).

The result was the emergence and growth of many new firms, conforming to the Schumpeterian model of innovation; although many large established firms with high levels of R&D were responsible for about half the major innovations between 1950 and 1980, the large firms' share of the market showed little change, but the top positions in the industry showed kaleidoscopic changes as one technology succeeded another (Table 9.1). In the European semiconductor industry, in contrast, very few new small firms or 'spin-off' firms entered; the new technology was introduced almost exclusively by subsidiaries of American firms or by large indigenous firms – Philips, Siemens, GEC, AEI (OECD 1968, Tilton 1971, Sciberras 1977, Braun & Macdonald 1982, Freeman *et al.* 1982).

The birth of the computer

The electronic computer, although closely related and partly dependent upon advances in electronic component technologies, in

Table 9.1 Leading US semiconductor firms, 1950–79.

	Merchant manufacturers, by share of world market		
Valves c.1950	Transistors 1955	Semiconductors 1965	Integrated circuits 1979
1 RCA	1 Hughes	1 Texas Instruments	1 Texas Instruments
2 Sylvania	2 Transistron	2 Motorola	2 National Semiconductors
3 GE	3 Philco	3 Fairchild	3 Motorola
4 Raytheon	4 Sylvania	4 General Instruments	4 Intel
5 Westinghouse	5 Texas Instruments	5 GE	5 Fairchild

Source: Braun & Macdonald (1982).

many respects may be regarded as having 'the most universal and far-reaching consequences' of all 20th century technological developments (Margerison 1978).

As with many key inventions, there is some doubt and dispute among historians of technology about the origin of the computer. It appears that the first practical computer, the Z3, was produced by Zuse in Germany in 1941, and that by 1942 his Z4 model was being used for aircraft design calculations. But this was an electromechanical device, as was the Harvard Mark 1 (also known as the Automatic Sequence Controlled Calculator – ASCC), produced by a team led by Aiken between 1937 and 1943; it became fully operational in May 1944. In 1943 and 1944 Bell Laboratories in the USA also produced two important devices, and in 1944 a British team at Bletchley Park produced a number of computers which appear to have involved important technical advances (Freeman *et al.* 1965, Margerison 1978, Randell 1980). All these, however, were electromechanical, and by the late 1930s it was already clear that electronic computers would be much faster and potentially more flexible. In Germany Zuse and Schreyer developed a crude model in 1942, but soon afterwards government support was withdrawn (Freeman *et al.* 1965, Zuse 1980). In 1944 a British team working in secret produced the Colossus, one of the first externally programmed electronic digital computers (Randell 1980).

It seems generally agreed that the first general purpose electronic computer was the ENIAC, developed for the American army to calculate trajectories of shells and bombs, and completed in 1946 by a team led by Mauchly and Eckert at the University of Pennsylvania. Shortly after that, the critical step towards the modern computer was made with the design of a practical stored-program computer, the EDVAC (Randell 1980). Even these early electronic machines performed arithmetic functions approximately a thousand times faster than electromechanical ones.

From 1945 to 1955 great progress was made in solving some of the problems of logic design, programming techniques, storage systems and appropriate peripheral devices (Freeman *et al.* 1965, OECD 1969). By 1951, the UNIVAC 1, the first commercial electronic computer, had arrived in the USA; developed by Eckert and Mauchly, who had left the University of Pennsylvania to set up their own company (acquired in 1950 by Remington Rand), it could handle both numerical and alphabetical data. In the UK the most important work in these years took place in London, Manchester, and Cambridge universities and the National Physical Laboratory. In 1951 a British computer, based partly on Cambridge University technology and known as the LEO (Lyons Electronic Office), was

the first to be used purely for commercial data handling (Margerison 1978).

Most of this work was heavily supported by government, especially for military purposes. Eckert and Mauchly's ENIAC was financed by the army; Forester's Whirlwind project at MIT, immediately after the war, by the navy (Brock 1975, Wildes & Lindgren 1985). Despite the advent of UNIVAC and LEO, by the early 1950s there was little commercial recognition of the potential of computers (Freeman *et al.* 1982). IBM's President Thomas Watson was still agnostic as to commercial prospects, and his own marketing department agreed; the success of UNIVAC, used to process the 1950 United States Census, took them by surprise, posing what seemed to be a major challenge by the rival Remington Rand Corporation (Sobel 1983). At this point IBM began in earnest to develop a computer to compete with the UNIVAC, releasing the 701 vacuum-tube machine in 1953. Already by 1955, IBM had a 56% market share against Remington Rand's 38%; by 1957 the shares were 78 and 16% (Brock 1975).

In 1958 the advent of 'second-generation' electronic computers utilizing transistors – pioneered by Sperry Rand, formed in 1955 by the merger of Remington Rand and Sperry, but emulated by IBM with their 7090 a year later – made clear the commercial potential of computers, and the industry began on a rapid growth path. This was marked in particular by the arrival in the mid-1960s of the minicomputer, with its combination of computing power and relatively low cost. New companies – Control Data, a breakaway from Rand, and Digital – began to emerge. Together with precomputer business machine firms, such as Sperry, Honeywell, Burroughs and NCR, that moved into the field by the early 1960s they formed the 'Seven Dwarfs' that competed with IBM (Brock 1975, Fishman 1981).

A similar technological step function took place in the mid-1970s with the introduction of the microprocessor; the large-scale integration of the components needed for the central processing unit of a computer onto a single microchip meant that the costs of computer hardware fell dramatically. These developments led to the emergence of an important new branch of the computer industry from the late 1970s, accompanied by its own process of swarming: the microcomputer (personal and home computer) industry. The beginnings came as early as 1975, when MITS, a small firm based in Albuquerque New Mexico, announced the Altair, a primitive machine, 'simply a metal box containing a power supply bolted to a large circuit board' that 'met the minimal definition of a computer and no more' (Freiberger & Swaine 1984).

Sold in kit form to enthusiasts, it was a runaway market success that surprised its inventors (ibid.); it 'breached the machine room door, and rivals emerged almost at once from garages all over the country' (ibid., 57).

These progressive technical developments led to major shifts in the organization of the new computer industry. In the US the mainframe industry of the 1950s and early 1960s was dominated by established firms from the accounting machine era of the third Kondratieff, notably Remington Rand (Sperry Univac) and IBM. But the minicomputer revolution of the mid-1960s, and the microcomputer revolution of the late 1970s, were both marked by the emergence of new firms which first developed and exploited the application of the new technologies: the Digital Equipment Corporation and Wang in the first, Apple, Commodore, Tandy (and Sinclair, Acorn and ACT in the UK) in the second.

This, simply, was because the established manufacturers failed to appreciate the potential of the new market. At the birth of the microcomputer both MITS and its competitors were hobbyist enterprises; none of the big companies wanted to build microcomputers:

> Without exception, the existing computer companies passed up the chance to bring computers into the home and onto the desk. The next generation of computers, the microcomputer, was created entirely by individual entrepreneurs working outside the established corporations. (Ibid., 18)

Kenneth Olsen, founder of Digital – a pioneer entrepreneur of the previous minicomputer revolution – rejected the idea of producing such a machine, saying he could see no use for a computer in the home (ibid.).

The result, inevitably, was a swarming of new companies during 1975, mainly in the San Francisco Bay area: IMSAI, Cromenco, MOS Technology, Microcomp Associates. Many, lacking entrepreneurial flair or management skills, soon crashed (ibid.). A significant element consisted of California campus dropouts from the 1960s era, who had an ideological commitment to computing for the people, and who met in the legendary Homebrew Club, which held its first meeting at Menlo Park in the heart of Silicon Valley in March 1975 (ibid.). This highly informal group – with no official membership, no dues, open to all – played a critical rôle in the exchange of ideas and the solution of technical problems at the birth of the new industry.

The outstanding commercial success story of this era was of course Apple, founded by two campus dropouts and Homebrew members, Stephen Wozniak and Steven Jobs, to market a home computer they developed early in 1976. Built with funds acquired by selling their own possessions, the Apple I sold a mere 200 through local stores and mail order. The Apple II, which they began to develop in the autumn of that year, was eventually financed by A.C. 'Mike' Markkula, a retired millionaire marketing director of Intel; it achieved Markkula's ambition by becoming the only company in business history to pass into the Fortune 500 within five years of foundation, reaching sales of $583 million in 1982 (Freiberger & Swaine 1984, 215, Rogers & Larsen 1984).

But the spawning of new companies did not end there. For the new hardware also required specially written software to make it usable, and above all to make it usable by the millions of new customers who had no previous computer experience. Some of the resulting companies were developed, like Apple, almost literally out of nothing: Digital Research was founded by Gary Kildall, an instructor at the Naval Postgraduate School at Pacific Grove in California, after he had developed (in 1973) the first commercial operating system for microcomputers, CP/M, in advance of the appearance of the Altair; BASIC was adapted for the Altair by two Harvard students, Bill Gates and Paul Allen, who then founded Microsoft; MicroPro, which developed WordStar, was founded by a refugee from the short-lived IMSAI Corporation, the second to market a microcomputer (Freiberger & Swaine 1984).

By this time the established companies had begun to try to catch up. The first, significantly, was not a computer firm at all but a retail chain: Tandy, which was originally founded as a leathercraft company in Fort Worth, Texas, in 1927, and had moved into electronics when it acquired a small, struggling chain of radio stores, Radio Shack, in 1962. It reluctantly developed its first machine, marketing it in August 1977 and only then realizing its potential (ibid.). The colossus of the industry, IBM, announced its Personal Computer only in August 1981; it was immediately recognized in the trade as a completely conventional product, using components bought in from existing producers and running established software which had been adapted for IBM in conditions of great secrecy by its proprietors (ibid.). Imitation, evidently, was the sincerest form of flattery: IBM, a company based for 30 years on a totally different concept of making and selling computers, had to borrow all the products of its competitors.

Advances in telecommunications

Parallel to these advances in computing, and dependent in large degree on the same developments in component technologies, came major changes in the transmission of information. The invention of the transistor was in part the outcome of research efforts at Bell Laboratories to develop improved electronic devices for telecommunications systems. Since then, there have been many advances in the basic elements of the basic telecommunications system: switching equipment, transmission equipment, and peripherals. And there have been major developments in wireless communications, most notably in satellite technology.

In switching equipment, the electromechanical Strowger systems continued to be replaced by crossbar exchanges, a more efficient electromechanical system developed in Sweden in 1915, and later by the first generation of electronic exchanges developed at Bell Laboratories in 1960. The crossbar system proved more compatible than Strowger with early attempts at computerization from the late 1960s. In the UK it was little used in the public network until the late 1960s; the Post Office attempted to develop an alternative system using hard-wired solid state circuitry which could only be changed by rewiring the system and was much less flexible than fully electronic exchanges (Hills 1984). In the USA, too, the earliest electronic switching systems used wired-logic, special purpose circuitry and technologies; but these were soon being replaced by stored program control (SPC) in which computer-like processors perform the necessary switching functions (US National Research Council 1984). The first was introduced by Western Electric in the USA in 1965; since then, more than 40 SPC switches have been developed by telecommunications equipment manufacturers round the world. The design of electronic automatic exchanges was closely related to the principles involved in computers (Tucker 1978; Dummer 1983). Their use occurred most rapidly in the USA; the first digital (System X) exchange was introduced into the British network in 1981. This was a major step towards digitalization of the telephone network, allowing all types of information to be transmitted and switched in digital form.

Developments in telecommunications transmission equipment allowed cables to carry a greater number of signals at any one time, and advances in semiconductors facilitated a major shift from the analogue to the digital mode of transmission, allowing more information to be transmitted more reliably and cheaply over similar transmission lines. Digital transmission was initially introduced in urban telephone networks in the USA to relieve trunking shortages without the high cost of installing additional cables; it was later extended to medium- and long-haul trunking (US National Research Council 1984). In turn, this enhanced the possibilities of digital data handling, leading incidentally to fierce competition between computer and telecommunications equipment manufacturers in such fields as local area networks and private branch exchanges: an example of the important principle of convergence of different information technologies, originally separate, towards the close of the fourth Kondratieff.

Technological advances also brought about many changes in the nature and range of transmission media, though copper cables remained at the centre of the transmission network in the early 1980s. From the 1940s microwave was developed as an alternative to coaxial cable for long-distance transmission; by the late 1970s, it accounted for over three quarters of the annual expenditure on long-distance transmission equipment by American common carriers. The development of satellite communications, developed originally under military contracts in the 1950s and 1960s, offered an alternative to cable and terrestrial microwave systems for long-distance and international telephone traffic. Since the mid-1960s space communications costs have fallen steadily although their range and quality has increased, rendering them an increasingly attractive medium for long distance telephone traffic, as well as broadcasting and remote sensing.

The other major advance has been optical fibre transmission. It has several times the signal capacity of coaxial cable of given dimensions, greater resistance to corrosion and greater immunity to electric interference as well as being based on silica, which is cheaper and more widely available than the copper used in conventional cables. Optical cables have the potential to provide a reliable and relatively cheap basis for distributing a broad range of communications signals in addition to conventional telephony ('the wired city' infrastructure of a fifth long wave), though the economics and politics of such potential broadband systems remained uncertain in the mid-1980s.

These optical-fibre transmission systems basically involve two product groups, the fibre cables themselves and the new opto-electronic components used to transmit and receive the signals along these cables. An early lead in optical fibres was taken by Western Electric and Corning Glass in the USA, which hold many of the early basic patents. In more recent years however, a number of other large telecommunications firms, including AT&T, ITT, NEC, Northern Telecom, NTT and Philips, have developed processes that are reported to be substantially different. In the component technologies, such as light-emitting diodes (LEDs) and lasers, much of the early work took place in the USA, but Japanese firms have played a major rôle in more recent years (US National Research Council 1984).

In line with these developments, the late 1970s and the 1980s have also seen the appearance of a wide range of increasingly sophisticated peripheral devices: the increasingly automated PABXs (Private Automatic Branch Exchanges); telex, facsimile, and videotex terminals and printers; memory telephones: and modems for domestic and business uses.

The main impact of these developments is greatly to enhance the range, reliability and potential of information transmission (whatever its type) across space while greatly reducing its cost. Hence they promise large improvements in capital productivity, much like the other elements of the new information technologies (Guy 1985). The shift towards digitalization allows closer links between computer and telecommunications systems and provides the necessary infrastructure for a potential range of significant new information industries; it may be viewed as the essential condition for any new long-wave upswing (Blackburn *et al.* 1985). These technical advances also provide a basis for the development of a wide range of new information and communication services such as mobile telephone networks and value added networks.

The consumer electronics sector

At the start of the fourth Kondratieff, and for more than a decade after the end of World War II, electronics-based New IT still largely consisted in the production of consumer goods, particularly for entertainment (Wilson 1964). There was still a growing market for radios, music reproduction and, above all, television. The early 1950s saw rapid expansion of the black and white television market, based on improvements in the basic technologies developed in the mid-1930s by EMI in the UK, Telefunken in Germany and RCA in the USA and, in the UK, on the postwar resumption of public broadcasting. Production was heavily concentrated in the hands of the original innovating companies with their large R&D resources. Colour television was an innovation of this period, mainly through America's RCA, with Germany's Telefunken playing a significant rôle (Freeman *et al.* 1982, National Research Council 1984); RCA began sales in 1954 but the product was slow to sell, because black and white television was still diffusing and there were few colour broadcasts. So it was not until the 1960s that RCA's investment began to pay off – and soon after, at the end of that decade, Japanese firms rapidly won the lion's share of the American market. Their success came not merely from imitation and low labour costs but from a wide range of both product and process innovations such as integrated-circuit technology, automated techniques in assembly, testing and handling, and personnel training at all levels, backed by large-scale R&D co-ordinated by the Ministry of International Trade and Industry. These resulted in considerable advances in quality, reliability and productivity compared with their American and European competitors (Freeman *et al.* 1982, Peck & Wilson 1982, National Research Council 1984).

This pattern was replicated in a wide range of consumer electronics products such as record and tape music reproduction systems, and, perhaps most spectacularly, in the video-cassette recorder, the major innovation of the 1970s. Although this was first developed for professional use in broadcasting studios by the American Ampex Corporation in 1956, the problem remained of how to develop it as a cheap mass-produced consumer product. During the 1960s a number of leading companies (RCA and Cartravision in the USA, Philips in Europe, Sony and Matsushita and others in Japan) worked on the problem of a cheaper machine, but still they were thinking mainly of industrial and broadcasting applications. In 1970 all these reported breakthroughs in developing helical cassette machines, but it was not until 1975 that Sony marketed its Betamax and 1977 that Japan Victor (51% owned by Matsushita) launched VHS (Video Home System), which soon came to dominate. Philips was the only real European contender but its V2000 format captured only a small part of the European market, and in 1984 it announced that it would market VHS machines, thus confirming the global triumph of this system (National Research Council 1984).

Office technology in the fourth Kondratieff

The strange fact was that for the first 30 years of the fourth Kondratieff the electronic revolution had a negligible influence on information technology in the place that might have seemed most obvious: the office. Of the four major innovations that affected office work between 1950 and 1980, two, the electric typewriter and the dictation machine, were not new at all: they represented technologies developed in the preceding Kondratieff, though brought into low–cost mass production only now. The dictation machine in particular was progressively miniaturized as the result of developments in tape recording – particularly the cassette, introduced in the early 1970s – and associated electronic technology, which together permitted a massive reduction in bulk of the equipment.

Two other pieces of technology were, however, new. The first, xerography or electrostatic copying, was an invention of 1937 by the American physicist Chester H. Carlson; it was at first ignored by the major corporations (which thought it had no commercial value) and was introduced commercially only in 1959. Like the electric typewriter in its developed form, it was American and controlled effectively by a monopolist, in this case the Xerox (previously Haloid) Corporation, during its first two decades of life. A runaway commercial success, it almost immediately displaced the stencil duplicator as a method of mass copying of documents and threatened carbon paper, the traditional method of making one or a few copies. Xerography is however, an interesting case of a special kind of innovation: deriving indirectly from photographic processes, it has no very direct technical relationship to the other strands in the history of New IT.

The other innovation, the electronic calculator, was, however, very much part of the mainstream story. Introduced during the early 1960s, it was rapidly miniaturized and reduced in price, thanks to the introduction of integrated circuitry. Its first manifestation was a machine of about the same bulk as a personal computer of the mid–1980s and costing about as much (in constant prices) as a fairly sophisticated personal computer. Within less than a decade, more sophisticated hand–held models weighing a few ounces were widely on sale in filling stations and similar outlets for about the price of a take–away pizza. This was only a particularly spectacular example of the bulk and cost reductions that followed the mass production of cheap dedicated chips in the early 1970s.

Conclusions

The distinctive features of the fourth Kondratieff were thus four. Firstly, new information technology became for the first time a key carrier technology of a long wave of economic development. Secondly, it did so through the full flowering of electronics, which had been born and partially applied during the third Kondratieff but was awaiting its full potential at that long wave's close. Thirdly, it started with separate and parallel developments in basic

componentry, in computing and in communications, which then became progressively united into one technological stream, particularly through the development of digital storage and transmission of information.

Fourthly, and significantly, it was earliest applied in two almost separate streams. First of all it resulted in a stream of consumer electronic products (television sets, high-fi record-playing equipment and records, tape recorders, FM radios) that followed from technological innovations of the period 1935–40, the application of which had been delayed by World War II. Then, however, the even newer advances following the discovery of the transistor were first applied to very expensive, state-of-the-art producer goods, at first mainly in military hardware, but also in early commercial computing, thence diffusing, through further technical development, and above all through drastic cheapening, to a wider range of consumer goods by the middle of the Kondratieff – a process mimicking that which occurred in the preceding long wave (the commercial application of radio) on a far vaster scale. Having completed the summary review of the development of the technologies, we turn now to their industrial impacts and in particular to the changing geography of production.