Chapter 6

Etched in Silicon: The 1980s

What was Happening in the 1980s

movies people were watching:
Amadeus
ET: The Extra Terrestrial
Platoon
Rainman
A Room With a View

TV shows people were watching:
"The Cosby Show"
"Dallas"
"Hill Street Blues"

music people were listening to:
Bobby McFerrin's "Don't Worry, Be Happy"

books people were reading:
In Search of Excellence by Thomas Peters and Robert Waterman
Garrison Keillor's *Lake Wobegon Days*

In much of the world, the 1980s was the decade in which Japanese consumer electronics became commonplace: stereos, televisions, VCRs, camcorders, CD players, video games, the Walkman, "boom boxes", personal computers, fax machines, cellular phones, and many other products manufactured by Hitachi, JVC, Mitsubishi, NEC, Nintendo, Panasonic, Sanyo, Sony, Toshiba, and other companies. The Japanese economy had grown vigorously after World War II: output increased 9.5 percent a year in the 1950s and 10.5 percent a year in the 1960s. In the 1970s the Ministry of International Trade and Industry (MITI) led a reorganization of the economy away from steel, ships, and chemicals and toward electronics and precision machinery. This helped bring about the "second economic miracle" of the 1980s.[1] Japanese companies pioneered many of the new electronic technologies, such as VCRs, videodisks, the Walkman, and compact disks, and the first commercial cellular-phone system anywhere in the world was the one put into service in Tokyo in 1979.

The burgeoning of consumer electronics owed much, of course, to the appeal of new products, such as personal computers and camcorders, and the new capabilities of already standard devices, such as stereo systems and telephones.[2] Perhaps even more important was the success of manufacturers

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[1]Richard Overy, ed., *Hammond Atlas of the 20th Century* (London: Times Books, 1996), pp. 156–157.

[2]Another factor was the generally high reliability of consumer-electronics products. In the mid 1990s a Harris poll found that Sony was the most respected brand among U.S. consumers [*Time* magazine, 17 November 1997, p. 56].

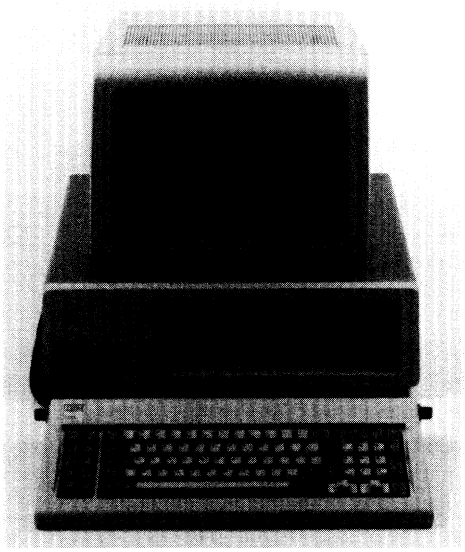

FIGURE 1. The IBM PC, introduced in 1981, rapidly became the industry standard. (IBM photo reproduced with permission.)

in providing more for the customer's dollar (or yen or mark). In the 1970s and 1980s, while the consumer price index in the United States tripled (that is, goods on average cost three times as much at the end of this period), the price of most consumer electronics products either remained constant or fell. Their 1990 cost in real terms, then, was one-third that of 1970.[3]

The 1980s was also the decade in which personal computers became ubiquitous. When the decade opened, many people thought of personal computers as something for hobbyists only. In 1981 IBM introduced its personal computer, and its disk operating system (DOS) quickly became the industry standard.[4] (See Figure 1.) The next year appeared the first IBM-PC

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[3]*The U.S. Consumer Electronics Industry in Review: 94 Edition* (Washington, DC: Electronic Industries Association, 1994), pp. 16, 24. The price of television sets fell substantially in this period, despite considerable improvement in the product.

[4]IBM gave a tiny company, Microsoft, the contract to produce the operating system; Microsoft obtained a suitable piece of software from another small company, Seattle Software Products, for $30,000; it was MS-DOS, provided with almost all IBM personal computers and compatible machines, that became the industry standard [Martin Campbell-Kelly and William Aspray, *Computer: A History of the Information Machine* (New York: Basic Books, 1996), pp. 254–255].

INTERVIEWER: The thing about the model-based approach is that you need accurate models. Has that been a problem?

THOMAS KAILATH: Yes, this has always been a barrier. People say you don't have the models, or that the models are very poor. However, this misses the point of mathematical modeling. It has been proved countless times over (in physics, chemistry, and engineering) that very simple models, which can be quite inaccurate, turn out to have tremendous predictive power. So you don't really need very fancy models. Simple models will do.[1]

JAMES KAISER: I'm one of those people who, when I've done some work, always says "Oh, somebody else is bound to have already done this before." I remember, I asked myself why, with all the work that was done in sampled data systems, with Bill Linvill, Ron Howard, and Bob Sittler, who were at MIT, and Lotfi Zadeh and John Ragazzini at Columbia (those were the two big sampled data schools), why those fellows didn't do more with the digital filtering. I think the problem was that at both places, they didn't have the economic means for implementing to any great extent the sampled data systems, which were primarily motivated by control system problems— mainly in radar, where you've got periodic signals arising from the antenna scan, the circular scan. After all, the integrated circuit had not yet come along.

After the development of the integrated circuit, however, it became possible for people to start thinking about implementation seriously. That's what made DSP take off![2]

[1]Thomas Kailath oral-history interview 13 March 1997, p. 32.

[2]James Kaiser oral-history interview 11 February 1997, p. 13.

clone, made by Compaq. In 1983 came the mouse and pull-down menus, with Apple's (commercially unsuccessful) Lisa, and that same year the IBM PC-XT became the first personal computer with a built-in hard-disk drive. Apple introduced the Macintosh in 1984, and its user-friendliness was copied in Microsoft's Windows software, released in October 1985. The number of personal computers worldwide increased from 1.3 million in 1980 to 115 million in 1990.[5] Computer software became a major industry, growing from annual sales of $140 million in 1981 to $1.6 billion three

[5]William Gates, "Personal computers in the Information Age", in *Britannica Yearbook of Science and the Future 1992* (Chicago: Encyclopaedia Britannica, 1991), pp. 144–153.

JAMES KAISER: Think of the designer of elements of a communication system: he or she has what I call the big parts box next to his or her desk. The parts box has a couple of different compartments, labeled "cheapest element," "next cheapest element," and "most expensive element." Remember, economics is always the name of the game. The engineer is going to try to use as much of the cheap stuff as possible. Well, for continuous filters design, the cheapest thing was wire. That's the cheapest thing going. Next were resistors and capacitors. Inductors were fairly expensive. The most expensive thing, however, was gain. With the vacuum tube supplying gain, you had to provide the filament supply and the plate supply (called the "C+") and so on. Consequently, filters were implemented primarily out of RLCs. Oh, maybe a little later you could get some active filters using miniature tubes, but it was mainly RLCs. These components cost money, so the design techniques for continuous filters were set up so that you were always trying to get the filter of minimum order to meet your specifications. Minimum order meant a minimum number of parts.

When we got the integrated circuit, it was like somebody completely changed the rules. The cheapest thing around now was gain—supplied by the transistor. You could lay down the resistors, that was easy. Capacitors were fairly easy. Inductors were still pretty hard, but you didn't really need those. You could leave those out of an instrument. The most expensive thing around, however, was the interconnection—the wire! All of the sudden, the tables were completely turned around.[1]

[1]James Kaiser oral-history interview 11 February 1997, pp. 13–14.

years later.[6] In the late 1980s email became common as personal computers connected to networks such as the Internet. (The number of Internet host computers grew from a thousand in 1984 to 150,000 in 1989.)[7]

The economic and technological advances took place in a fairly stable political setting: Ronald Reagan (followed by his former running-mate George Bush), Margaret Thatcher, Helmut Kohl, and François Mitterand led their countries through most of the 1980s and into the 1990s. The European Economic Community, which expanded by the addition of three nations in the 1970s and three more in the 1980s, rivaled the superpowers

[6]Campbell-Kelly and Aspray *op. cit.*, p. 260.

[7]Campbell-Kelly and Aspray *op. cit.*, p. 297.

in population and economic strength.[8] The decade ended, however, with the dissolution of the Soviet Union and the downfall of most Communist regimes in eastern Europe, epitomized for many by the opening of the Berlin Wall in November 1989. There were far-reaching changes in political and economic institutions in China, though the crushing of a protest at Peking's Tiananmen Square in June 1989 was a set-back for political freedom.[9] The first launch of the Space Shuttle *Columbia* in 1981 came to be overshadowed for most people by the explosion, shortly after launch, of the Shuttle *Challenger* in 1986. The 1984 breakup of AT&T into a long-distance company and seven regional operating companies ("Baby Bells") affected almost everyone in the United States.[10]

One of the exciting new technologies at the start of the decade was videodisk, available in a variety of systems. They were of two types: systems in which an electrode sensed differences in capacitance, pioneered in the RCA VideoDisc, and systems with optically encoded information read by a laser, pioneered in Philips Laservision.[11] None of these achieved great market success,[12] though development of the latter type contributed to one of the most successful consumer products of all time, the CD player.

1983 was the year Philips and Sony, rival companies that collaborated in bringing the new technology to market, began selling CD players. Its technical features, some of which were described in Chapter 1, drew on several decades of advances in signal processing, using, for example, the type of error-correction coding invented by Irving S. Reed and Gustave Solomon in 1960 and incorporating a 16-bit analog-to-digital converter and digital filters of various sorts.[13] Besides setting a new standard for audio fidelity—

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[8]David Reynolds, "Europe divided and reunited, 1945–1995" (in T.C.W. Blanning, ed., *The Oxford Illustrated History of Modern Europe* (Oxford: Oxford University Press, 1996), pp. 279–304).

[9]Signal-processing engineers may have noted that the fax machine was an important tool of the student revolt in China in 1989 [Steven Lubar, *Infoculture: The Smithsonian Book of Information Age Inventions* (Boston: Houghton Mifflin, 1993), p. 10].

[10]One effect was to make the telephone, for the first time, a consumer electronics product; until then telephones had been leased from the phone company.

[11]Margaret B.W. Graham, *The Business of Research: RCA and the VideoDisc* (Cambridge: Cambridge University Press, 1986), pp. 14–24.

[12]One cause of the market failure of the videodisk in the early 1980s was that its introduction came just at the time that VCRs were catching on with consumers [Graham *op. cit.*, pp. 213–219].

[13]Peter J. Bloom, "High-quality digital audio in the entertainment industry: an overview of achievements and challenges" (*IEEE ASSP Magazine*, vol. 2 (1985), no. 4, pp. 2–25), and Fred Guterl, "Compact disc" (*IEEE Spectrum*, vol. 25 (1988), no. 11, pp. 102–108).

Bede Liu: In 1967 or so, I proposed to NASA a way to implement digital filters using delta modulation, without the multiplier, because in delta modulation, it is easy to do multiplication by one bit. That was not funded. But, two or three years later, I was working with Abe Peled [a graduate student] and I asked him to look at it again. He came back a couple of days later and said, "This is a great idea. It works." We continued working on it and he said, "Oh yeah, you can do this sort of thing; that will be very good." It is now the scheme most people call distributed arithmetic.

... It turned out some others thought of the same idea just around that time, maybe even a little bit ahead of us, but for some reason they did not receive wide publicity. Stan White at Rockwell was very interested in this. He dubbed the scheme the "Princeton Multiplier."[1]

[1]Bede Liu oral-history interview 10 April 1997, pp. 14–15.

consumers now expect CD-quality sound from other products—this technology contributed to the development of a variety of other optical storage media, such as the CD-ROM (Read Only Memory optical-disk for computers), which was introduced by Philips and Sony in 1984, and the Digital Versatile Disk (DVD), which began to be marketed in the late 1990s. Another form of digital audio, digital audio tapes, began to be marketed in the mid 1980s, but were slow in gaining popularity.

The CD player, which for every second of music performed prodigious computations, would not have been economically feasible before the era of integrated circuits and solid-state lasers,[14] and no doubt the biggest story in signal processing in the 1980s was the design and production of integrated circuits, especially single-chip DSPs. It was, of course, possible to use general-purpose chips, but a chip designed specifically for signal-processing operations could do the job much faster. And for real-time signal processing, where a signal must be processed as fast as it arrives, speed is not just desirable, but requisite.

A number of factors determine how rapidly a single-chip DSP carries out an algorithm. Processor speed, measured in millions of instructions per second (MIPS), is obviously important. So is the use of dedicated multiplier units, which perform multiplications in a single cycle, not, as in traditional

[14]The first CD players offered by Philips contained 20 ICs each, though a long-term design goal was to reduce this to a single IC [Guterl *op. cit.*].

computer architectures, through a series of shift-and-add cycles. Still greater speed comes from the use of special instructions that involve several operations in a single cycle, such as multiplying two numbers and simultaneously adding the previous product to a total. Also, there is the use of pipelined architectures, which permit the simultaneous execution of different stages of a process.[15] As a result of these and other design features, the performance of single-chip DSPs has consistently exceeded that of microprocessors with arithmetic co-processors by more than an order of magnitude.[16]

In the early 1980s there appeared quite a few single-chip DSPs. Particularly successful were the AMI S2811, the Intel 2920, the NEC muPD7720, and TMS32010 from Texas Instruments.[17] The last named was the first in the highly successful and continuing TMS320 series. (See Figure 2.) In 1984 AT&T began marketing DSPs with the DSP32, which was the first 32-bit floating-point DSP.[18] Particularly successful in audio products was the Motorola 56000, introduced in 1985.[19]

As the applications of signal processing increased, great efforts were made to improve the performance of DSPs. Innovative algorithms were introduced, such as the fast Hartley transform, developed by Ronald Bracewell in 1984,[20] and the arithmetic Fourier transform, introduced by Donald Tufts and G. Sadasiv.[21] Some algorithms were designed specifically to match hardware capabilities, such as the Winograd discrete Fourier transform, which reduced multiplications at the expense of increased addi-

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[15]Gene Frantz and Panos Papamichalis, "Introduction to DSP solutions" (*Texas Instruments Technical Journal*, vol. 13 (1996), no. 2, pp. 5–16).

[16]Edward A. Lee, "Programmable DSP architectures: part I" (*IEEE ASSP Magazine*, vol. 5 (1988), no. 4, pp. 4–19).

[17]Craig Marven and Gillian Ewers, *A Simple Approach to Digital Signal Processing* (New York: John Wiley & Sons, 1996), p. 11.

[18]Lee *op. cit.*

[19]Mark Kahrs, "Professional and consumer gear: hardware & software" (*IEEE Signal Processing Magazine*, vol. 14 (1997), no. 5, pp. 51–57).

[20]Ronald N. Bracewell, "The Fourier transform" (*Scientific American*, vol. 260 (1989), no. 6, pp. 86–95). The original Hartley transform was conceived by Western Electric researcher Ralph Hartley in 1942 as an alternative to the Fourier transform in analyzing a function in terms of sine and cosine functions.

[21]Donald W. Tufts and G. Sadasiv, "The arithmetic Fourier transform" (*IEEE ASSP Magazine*, vol. 5 (1988), no. 1, pp. 13–17).

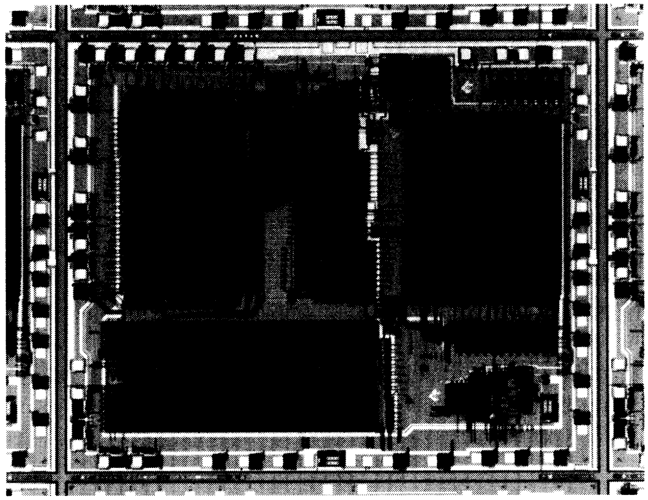

FIGURE 2. This was the first single-chip DSP manufactured by Texas Instruments. (Texas Instruments photo reproduced with permission.)

tions.[22] The decade of the 1980s also saw much work on adaptive IIR (infinite-impulse-response) filters and on nonlinear filters.[23]

A great deal of attention was given to alternative ways of carrying out multiplication, such as cellular arrays, memory intensive policies, homomorphic systems, and modular arithmetic, which led in the late 1980s to the design of dedicated multiply, multiply/accumulate, and numeric processor chips.[24] For algorithms involving trigonometric, logarithmic, or exponential functions, the CORDIC (COordinate Rotation DIgital Computer) algorithm received renewed attention as an alternative to the conventional multiply-and-add hardwares.[25] Another alternative architecture that at-

[22]David J. DeFatta, Joseph G. Lucas, and William S. Hodgkiss, *Digital Signal Processing: A System Design Approach* (New York: John Wiley, 1988), p. 3.

[23]John J. Shynk, "Adaptive IIR filtering" (*IEEE ASSP Magazine*, vol. 6 (1989), no. 2, pp. 4–21), and V. John Mathews, "Adaptive polynomial filters" (*IEEE Signal Processing Magazine*, vol. 8 (1991), no. 3, pp. 10–26).

[24]Gin-Kou Ma and Fred J. Taylor, "Multiplier policies for digital signal processing" (*IEEE ASSP Magazine*, vol. 7 (1990), no. 1, pp. 6–20).

[25]Yu Hen Hu, "CORDIC-based VLSI architectures for digital signal processing" (*IEEE Signal Processing Magazine*, vol. 9 (1992), no. 3, pp. 16–35), and Jack E. Volder, "The CORDIC trigonometric computing technique" (*IEEE Transactions on Electronic Computers*, vol. 8 (1959), pp. 330–334).

INTERVIEWER: What happened when these chips became available?

BEDE LIU: People underestimated how difficult it was to program them. They did not realize that you need a whole support structure to do it. It's not that you can plug it in, twiddle a few knobs and it works. Assembly-language programming was not widely taught, there were no compilers. You could not write in high-level language and then compile. That came much later. There were some transitions to go through. I think something like the Intel 2920 was actually very useful for a while, but they did not realize—this is the story I heard—that each of these products required multi-million-dollar support. So some of these failed. I think Texas Instruments succeeded because of this. Once the chip is out, they have a developing board, an interface board; they have a whole system to use. Those were in the mid-'80s—it took roughly five years for those to become useful.[1]

[1]Bede Liu oral-history interview 10 April 1997, pp. 25–26.

tracted interest in the 1980s was distributed arithmetic. Invented independently in about 1970 by Alain Croisier and colleagues in France and by Shalhav Zohar in the United States, distributed arithmetic is well suited to the usual sum-of-products computation.[26] The 1980s also saw increased interest in various schemes of parallel computation. Parallel processing for the FFT had been developed in the mid 1970s,[27] and in the 1980s considerable work on parallel processing led to the adoption of new algorithms.[28]

Signal processing played an important part in what became quite apparent in the 1980s: an increasingly globalized culture. People in countries

[26]Stanley A. White, "Applications of distributed arithmetic to digital signal processing: a tutorial review" (*IEEE ASSP Magazine*, vol. 6 (1989), no. 3, pp. 4–19). The name 'distributed arithmetic' was introduced by Hans Wilhelm Schuessler; see Manfred Buettner and Hans Wilhelm Schuessler, "On structures for the implementation of the distributed arithmetic" (*Nachrichtentechnische Zeitschrift*, vol. 29 (1976), pp. 472–477).

[27]Bernard Gold and Theodore Bially, "Parallelism in fast Fourier transform hardware" (*IEEE Transactions on Audio and Electroacoustics*, vol. AU-21 (1973), pp. 5–16).

[28]See, for example, Alfred Bruckstein and Thomas Kailath, "An inverse scattering framework for several problems in signal processing" (*IEEE ASSP Magazine*, vol. 4 (1987), no. 1, pp. 6–20); Peter Strobach, "New forms of Levinson and Schur algorithms" (*IEEE Signal Processing Magazine*, vol. 8 (1991), no. 1, pp. 12–36); and Thomas Kailath and Ali H. Sayed, "Displacement structure: theory and applications" (*SIAM Review*, 1995, pp. 297–386).

around the world very often experienced the same television programming, the same movies, the same music, and the same computer games, and all of these products involved signal processing. Television became even more influential: in 1992 there were 153 television sets for every 1000 people worldwide, 490 per thousand in developed countries. In 1986 television was played, on average, eight hours per day in every U.S. home.[29] Some 700 million people watched the marriage of Prince Charles and Lady Diana Spencer in 1981, and the next year three or four times that many watched the World Cup soccer final.

The decade opened with enthusiasm for videotex, which was to put inexpensive computer terminals in the homes of millions of people, who could use the terminals, connected to large computers through telephone lines, to view news, sports, and other information, as well as do shopping and banking. In the late 1970s many national PTTs (post, telegraph, and telephone administrations) and dozens of private companies designed videotex systems. There were problems, notably the high cost of a terminal (or a decoder to attach to one's television set) and the slowness with which high-resolution graphics appeared on the screen. The first videotex system was British Telecom's Prestel. Launched in 1979, it had only 48,000 subscribers five years later. Of the European videotex systems, the only one to become at all popular in the 1980s was the French Teletel, which used a terminal called "Le Minitel", provided to users free of charge.[30] In the late 1990s personal computers attached to the Internet achieve many of the purposes of videotex, but one should remember that PCs were hardly known when the videotex systems were first planned.

The effort to devise more efficient coding for videotex graphics exemplifies the increased attention in the 1980s to image processing. Other applications included fax machines, camcorders, radar, enhancement of satellite photos, and medical imaging. For example, CT (computerized tomography) scanners, introduced in the 1970s, became faster and more economical, and MRI (magnetic resonance imaging) scanners began to be used in hospitals in the early 1980s.[31] Signal processing techniques were used also to make sonograms (diagnostic ultrasound images) more useful.[32]

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[29]Overy *op. cit.*, p. 188.

[30]Carol Fletcher, "Videotex: return engagement" (*IEEE Spectrum*, vol. 22 (1985), no. 10, pp. 34–38).

[31]*IEEE Spectrum*, vol. 25 (1988), no. 11, p. 73.

[32]Roman Kuc, "Processing of diagnostic ultrasound signals" (*IEEE ASSP Magazine*, vol. 1 (1984), no. 1, pp. 19–26).

Hans Georg Musmann: We learned that by going digital and then reducing the bit rate, you can reduce the transmission time, and thus the cost. In the meantime, the facsimile machines were increasing in resolution even though they were still analog. But one page required about fifteen minutes for transmission. I think at that time the transmission cost to the United States was about twenty to thirty D-marks, so it was very expensive to transmit one image.

Interviewer: Was this commercially used at that time?

Musmann: Only for police and industry because it was too expensive for most people. Also the machines were very expensive: ten thousand to twenty thousand D-marks. But we recognized that there was potential development in the facsimile, which was related to the development of printers for computers. Computers require printers, and facsimile machines are similar to a printer. So there was a synergy between these two developments.

... The company of Dr. Hell [Rudolf Hell GmbH], which was in Kiel, constructed facsimile machines for the police, and we were in contact with them. We found that it is possible to reduce the number of bits for presenting an image by about a factor of ten. This was relatively complicated; it was the Ph.D. work of Dieter Preuss, and it is still used as reference today. There was a parallel development in both the United States and Japan.

... It was the Japanese industry which recognized the potential behind the facsimile and pushed this to make products out of it. There was a special need for Japan; the Western countries already had Telex.[1]

[1]Hans Georg Musmann oral-history interview 30 August 1994, pp. 10–13.

In the mid 1980s black-and-white movies began to be colorized with the help of a video signal-processing system.[33] (Though deplored by most cineasts, the method certainly increased the number of old movies shown on television.)[34] Toward the end of the decade many VCRs contained digital memory circuits for generating still-frames and other special effects.[35]

It was in the 1980s that the fax machine became common in offices. This resulted in part from more efficient coding, less expensive hardware,

[33]The system built by Color Systems Technology contained more than 20 microprocessors working in parallel [*IEEE Spectrum*, vol. 22 (1985), no. 10, p. 30].

[34]Studies showed that TV viewers trying different channels for something to watch were much more likely to stop for a color movie than a black-and-white movie.

[35]*U.S. Consumer Electronics Industry: 94 Edition op. cit.*, p. 23.

and the adoption of international standards. As early as 1968 there was an international standard for fax transmission. This standard, for the so-called Group 1 machines, and the next, adopted in 1976 for Group 2 machines, were for analog coding. In 1980 came the first international digital standard, for Group 3 machines. Y. Wakahari and T. Yamada in Japan and Thomas S. Huang in the United States were among the contributors to the Group 2 and Group 3 compression standards. There followed in 1984 the standard for Group 4 machines, which was to accommodate the new ISDN (see below). From 1980 to 1992 the cost of a digital fax machine fell by a factor of 30, and in the United States the market for fax machines grew from a half million units (annual sales) in 1985 to six million in 1991.[36]

In the 1980s image processing became a recognized technical specialty. The first books on image coding—such as *Computer Techniques in Image Processing* by Harry Andrews, *Picture Bandwidth Compression* edited by Thomas Huang and Oleh Tretiak, and *Image Transmission Techniques* edited by William K. Pratt—appeared in the 1970s.[37] John Limb and Art Murphy showed how to measure the speed of moving objects, a result later used by Arun N. Netravali and John D. Robbins to introduce motion-compensated television coding.[38] Hans Georg Musmann demonstrated video transmission using only one 64-kbps speech channel and introduced a number of techniques for video transmission at low bit-rates, including scene analysis and object-dependent parameter coding.[39] Roger Y. Tsai and Thomas

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[36]Henry Petroski, *Invention by Design: How Engineers Get from Thought to Thing* (Cambridge, MA: Harvard University Press, 1996), pp. 113–118.

[37]Harry C. Andrews, *Computer Techniques in Image Processing* (New York: Academic Press, 1970); Thomas S. Huang and Oleh J. Tretiak, eds., *Picture Bandwidth Compression* (New York: Gordon and Breach, 1972), and William K. Pratt, ed., *Image Transmission Techniques* (New York: Academic Press, 1979). Another important book of the 1970s was Harry C. Andrews and Bobby R. Hunt, *Digital Image Restoration* (Englewood Cliffs, NJ: Prentice-Hall, 1977). See Hans Georg Musmann oral-history interview 30 August 1994.

[38]John O. Limb and H. Arthur Murphy, "Measuring the speed of moving objects from television signals" (*IEEE Transactions on Communications*, vol. 23 (1975)), and Arun N. Netravali and John D. Robbins, "Motion-compensated television coding: part I" (*Bell System Technical Journal*, vol. 58 (1979), pp. 631–669).

[39]Hans Georg Musmann and Juergen Klie, "TV transmission using a 64 kbit/s transmission rate" (*International Conference on Communications*, 1979, pp. 23.3.1–23.3.5) and Hans Georg Musmann, "Predictive image coding" (in William K. Pratt, ed., *Image Transmission Techniques* (New York: Academic Press, 1979), pp. 73–112). See also Hans Georg Musmann, Michael Hötter, and Jörn Ostermann, "Object oriented analysis synthesis coding of moving images" (*Signal Processing; Image Communication*, vol. 1 (1989), pp. 117–138) and Hans Georg Musmann, "A layered coding system for very low bit rate video coding" (*Signal Processing: Image Communication*, vol. 7 (1995), pp. 267–278).

Huang achieved valuable results in estimating 3-dimensional motion from 2-dimensional images.[40] In 1984 appeared the influential text *Multidimensional Digital Signal Processing* by Dan Dudgeon and Russell Mersereau, and in 1988 Arun Netravali and Barry Haskell published a comprehensive presentation of the theoretical and practical aspects of image coding.[41]

The improvement of image processing was facilitated by the use of common test images, which made it easier to compare the performance of different algorithms or image processing systems. These test images, four of which are shown in Figure 3, were chosen for their inclusion of a wide range of visual features such as textures, shadings, and colors. For the study of motion-picture systems there are standard video sequences. (Similarly, the speech-processing community has employed standard samples of speech.)[42]

A major achievement of the 1980s was JPEG, the international standard for digitizing and compressing still pictures. The Joint Photographic Experts Group, under the auspices of the International Organization for Standardization and the International Electrotechnical Commission, elicited the views of experts from around the world and reached agreement on a standard that has been widely adopted. The success of JPEG inspired efforts to reach standards for moving images, which, as we will see in Chapter 7, was achieved in the 1990s in the form of MPEG1 and MPEG2.[43]

Automated image-recognition is one of the tasks signal-processing engineers have tackled. There are numerous contexts in which this would be useful, as in detecting missile-sites in aerial photographs, recognizing a person from a video image, or finding pictures of interest in a large photograph collection. It has, however, proved extremely difficult to write traditional computer-programs to analyze images. A different approach is to construct neural networks that can be trained to do the job.

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[40]Roger Y. Tsai and Thomas S. Huang, "Estimating three-dimensional motion parameters of a planar patch" (*IEEE Transactions on Acoustics, Speech, and Signal Processing*, vol. 29 (1981), pp. 1147–1152).

[41]Dan E. Dudgeon and Russell M. Mersereau, *Multidimensional Digital Signal Processing* (Englewood Cliffs, NJ: Prentice-Hall, 1984), and Arun N. Netravali and Barry G. Haskell, *Digital Pictures: Representation and Compression* (New York: Plenum Press, 1988).

[42]An example from the early 1990s is the Oregon Graduate Institute Multi-language Telephone Speech Corpus, designed for language identification research [Yeshwant Muthusamy, Etienne Barnard, and Ronald Cole, "Reviewing automatic language identification" (*IEEE Signal Processing Magazine*, vol. 11 (1994), no. 4, pp. 33–41)].

[43]William Sweet, "Chiariglione and the birth of MPEG" (*IEEE Spectrum*, vol. 34 (1997), no. 9, pp. 70–77)

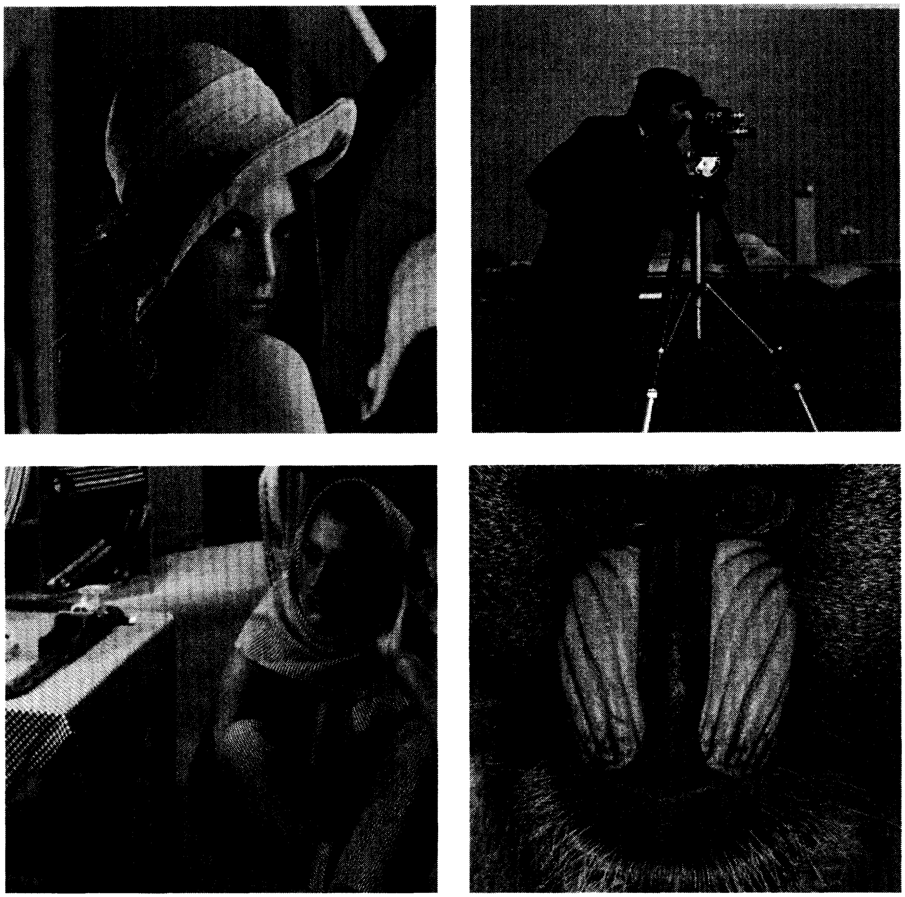

FIGURE 3. These are four common test images: Lena (or Lenna), the MIT cameraman, Stripes, and the mandrill. The last has been used especially in studying the processing of color images. (Lena image reproduced by permission of Playboy magazine.)

Work on neural networks, which began in the 1940s, was motivated by the wish to emulate the way the human brain works. While a traditional computer consists of a central processing unit carrying out a specified set of operations sequentially, a neural network consists of a large number of processing units working simultaneously and interconnected by multiple links. The basic unit, called a neuron, may have the structure shown in Figure 4.

Two milestone achievements of the 1950s were Frank Rosenblatt's perceptron (a simple neural network that decides which of two classes a given pattern belongs to) and Bernard Widrow's adaline (adaptive linear el-

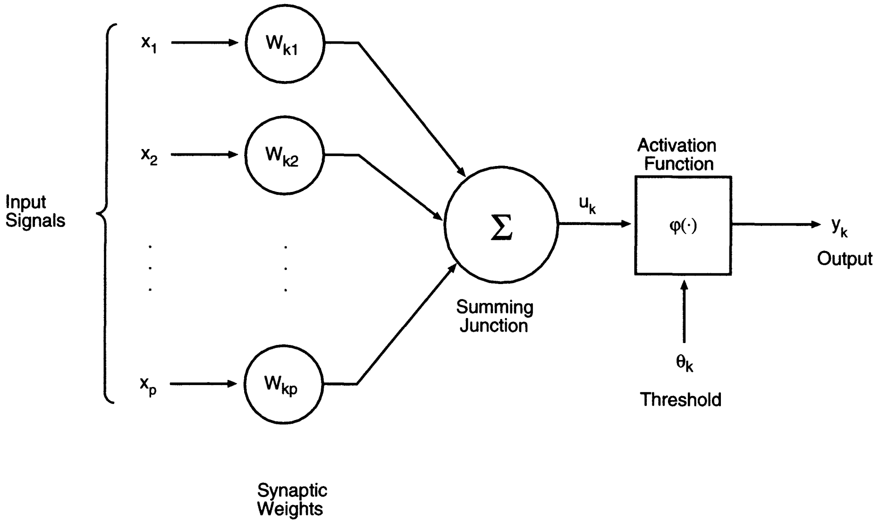

FIGURE 4. The neuron receives input signals and produces an output signal. For each input there is a weighting factor, and the activation of the neuron may be influenced by a threshold signal. (Redrawn after figure on p. 8 of Simon Haykin, *Neural Networks: A Comprehensive Foundation* (New York: Macmillan, 1994).)

ement). Engineering interest in neural networks flagged in the 1960s and 1970s, but was strongly revived in the 1980s. Among the causes were new algorithms, the new capability to implement neural networks in very-large-scale integrated (VLSI) circuits, and the belief that massive parallelism was needed for speech and image recognition. Some of the most important new algorithms appeared first in two landmark publications: John J. Hopfield's 1982 paper on recurrent networks, and a 2-volume text, edited by David E. Rumelhart and James L. McClelland and published in 1986, on parallel distributed processing.[44] It might also be pointed out that the 1987 tutorial ar-

[44]Simon Haykin, "Neural networks expand SP's horizons" (*IEEE Signal Processing Magazine*, vol. 13 (1996), no. 2, pp. 24–49), and Richard P. Lippmann, "An introduction to computing with neural nets" (*IEEE ASSP Magazine*, vol. 4 (1987), no. 2, pp. 4–22). The publications referred to are John J. Hopfield, "Neural networks and physical systems with emergent collective computational abilities" (*Proceedings of the National Academy of Sciences USA*, vol. 70 (1982), pp. 2554–2558) and David E. Rumelhart and James L. McClelland, eds., *Parallel Distributed Processing: Explorations in the Microstructure of Cognition* (Cambridge, MA: MIT Press, 1986). Rumelhart and McClelland described the back-propagation algorithm that was invented by Paul Werbos and first published in his economics Ph.D. thesis at Harvard; this is the most widely used algorithm in the field of neural networks today [Widrow personal communication 2 February 1998].

INTERVIEWER: You then somehow have to code the shape of the object?

HANS GEORG MUSMANN: Yes, and that is the problem we're working on today. In 1989 we suggested object-based coding instead of block-based coding. We represented each moving object by three sets of parameters: the shape, the motion, and the color of the object. If you transmit these parameters, you can synthesize the image at the receiver. The coder estimates the motion of an object, and also tries to estimate the three-dimensional shape. The shape is represented by a wire frame. The color is projected on top of the wire frame surface.

We have developed algorithms which automatically estimate the three-dimensional shape and the three-dimensional motion of an object. Then we move these model objects and calculate a projection of the changed scene. Thus we generate a moving image sequence, which is used for prediction, parallel to the real one. By this technique, we have reduced the areas of prediction errors to only four percent of each image. Ninety-six percent is predicted correctly and needs no transmitted information. This makes it possible to transmit moving images with a bit rate in the range of 8 kbit/s to 64 kbit/s. That means you can transmit moving images in the mobile telephone system.[1]

[1]Hans Georg Musmann oral-history interview 30 August 1994, pp. 26–27.

ticle written by Richard Lippmann and published in the *IEEE ASSP Magazine* became one of the most referenced papers in the neural network literature.[45]

The field was enlarged in several ways in the 1980s. Building on the work of Rosenblatt, numerous researchers devised sophisticated multi-layer perceptron (MLP) networks. A different type, the radial basis function (RBF) network, came to be quite popular in the 1980s. Both the MLP and RBF networks were static, in the sense that the processing units, or nodes, were memoryless, so that the network could draw on current input only. Dynamic networks, by contrast, could draw on past or future inputs or outputs. (The use of delay lines makes future inputs or outputs available.). The so-called Hopfield network became the most widely used type of dynamic network.[46]

[45]Don R. Hush and Bill G. Horne, "Progress in supervised neural networks" (*IEEE Signal Processing Magazine*, vol. 10 (1993), no. 1, pp. 8–39).

[46]Hush and Horne, *op. cit.*

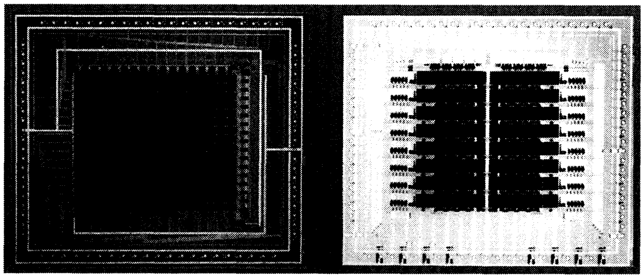

FIGURE 5. Two neural-network chips developed at Lincoln Laboratory in 1988. The one on the left is a perceptron classifier and the one on the right is a feature-map quantizer, or perhaps the other way around. (Lincoln Lab photo reproduced with permission.)

Quite a few potential applications of neural networks in automatic speech recognition, automatic target recognition, robotic vision, and other areas were shown to be at least feasible, if not yet practical.[47] The use of VLSI reached fruition in 1988, when neural-network chips were developed both at Bellcore and Lincoln Laboratory.[48] Figure 5 shows two chips developed at Lincoln Lab that were charged-couple devices and that used analog signal processing for vector multiplication.[49]

The 1980s saw the evolution of the Integrated Services Digital Network (ISDN) from concept to large-scale implementation. The overall aim of ISDN was to maximize the capabilities of the public switched telephone network, allowing transmission of voice, data, and image on a single network.[50] Digital transmission throughout, from subscriber to subscriber, would make this possible, and the standards adopted would be independent of the transmission medium or distance involved. Agreement on standards was reached through the International Telecommunication Union, with an important set of recommendations appearing in 1985. Among the areas of digital signal processing that were vital to ISDN were digital filters, adap-

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[47]Freeman *op. cit.*, pp. 232–233.

[48]John R. Pierce and A. Michael Noll, *Signals: The Science of Telecommunications* (New York: Scientific American Library, 1990), p. 4, and Eva C. Freeman, ed., *MIT Lincoln Laboratory: Technology in the National Interest* (Lexington, MA: MIT Lincoln Laboratory, 1995), p. 233.

[49]Freeman *op. cit.*, p. 233.

[50]*Britannica Yearbook of Science and the Future 1991* (Chicago: Encyclopaedia Britannica, 1990), p. 325.

Lawrence Rabiner: I think the technology is so mature that it's second nature to everybody. Everyone you hire is absolutely steeped in the technology, knows it inside out, and uses it without thinking.

Interviewer: Did this maturing take place in the early 80s?

Rabiner: Probably in the early- to mid-'80s. When people come in now, they are just so good with it, it's just fundamental. It's being taught to undergraduates, throughout almost the entire world. People don't even think about it, it's like programming.[1]

Charles Rader: A very important development in the '70s and '80s was the importance of the relation between algorithms and architectures....

In specialized signal processing, where you know what the algorithm is and you're willing to commit it to hardware, you can have a lot of multiplications, additions, registers, divisions, and square roots, and so on, all working together, all working at the same time. And then one of the issues is how do these things all get connected together so the results of one computation could get to where they're needed next, and things can all be kept busy at the same time.[2]

[1]Lawrence Rabiner oral-history interview 13 November 1996, p. 41.

[2]Charles Rader oral-history interview 27 February 1997, p. 49.

tive filters, and signal analysis and recognition.[51] In 1997 an ISDN line allowed a transmission rate of 64,000 bits per second.[52]

Some achievements of the 1980s might be mentioned. Blind linear equalization moved from concept into practice.[53] The concepts of multirate signal processing (decimation and interpolation of signals) became much better and more widely understood through the 1983 text *Multirate Digital Signal Processing* by Ronald Crochiere and Larry Rabiner.[54] In 1984 Bishnu

[51]Maurice Bellanger, "New applications of digital signal processing in communications" (*IEEE ASSP Magazine*, vol. 3 (1986), no. 3, pp. 6–11).

[52]Limitations within the telephone network, however, sometimes mean that data speeds are limited to 56,000 bits per second (*IEEE Spectrum*, vol. 32 (1995), no. 6, p. 25).

[53]John R. Treichler, I. Fijalkow, and C. Richard Johnson, Jr., "Fractionally spaced equalizers" (*IEEE Signal Processing Magazine*, vol. 13 (1996), no. 3, pp. 65–81).

[54]Ronald E. Crochiere and Lawrence R. Rabiner, *Multirate Digital Signal Processing* (Englewood Cliffs, NJ: Prentice-Hall, 1983).

Atal and Manfred Schroeder published an important paper on code-excited linear prediction (CELP), which today is ubiquitous for speech coding at 4 to 16 kbps.[55] In 1988 Robert McAulay and Thomas Quatieri introduced the sinusoidal transform coder (STC), which outperforms LPC in midrate vocoding.[56]

Many advances in digital signal processing were stimulated by the satellite-communications business and by space programs. Packet-speech conferencing over a satellite network was demonstrated in 1982.[57] Space communications relied on a whole range of DSP techniques, and NASA's Deep Space Network, arrays of antennas located around the world, continued to perform prodigies of signal extraction (the 1989 Voyager images of Neptune, for example, traveling across almost three billion miles of space).[58]

Electroacoustic transducers appeared to be a mature technology in 1970, yet the 1970s and 1980s were years of rapid progress. Fiber-optic sensors saw great improvement and were used in a variety of instruments besides in communications. (See Figure 6.) Silicon transducers, that is, sensors on silicon chips, were developed with the aim of being able to place both sensor and signal-processing circuitry on a single chip. This was achieved in 1983 when M. Royer and coworkers at Honeywell demonstrated a fully integrated acoustic sensor.[59] The electret microphone, first commercialized by Sony in 1968, was improved, and other types of electret transducers were developed. A breakthrough of the 1970s was the commercialization of piezopolymer transducers, first by Pioneer Corporation in Japan.[60]

Audio engineering saw many advances in the 1980s. In the United States stereo was added to television broadcasting in 1985. Though digital audio tape was not a great success in the consumer marketplace, it was adopted by sound engineers in audio, television, and movie studios, as

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[55]Biing-Hwang Juang, "Speech, audio, and acoustic processing for multimedia" (*IEEE Signal Processing Magazine*, vol. 14 (1997), no. 4, pp. 34–36). The paper by Atal and Schroeder is "Stochastic coding of speech at very low bit rate" (*Proceedings of the International Conference on Communications*, Amsterdam, 1984, pp. 1610–1613).

[56]Freeman *op. cit.*, p. 231.

[57]Freeman *op. cit.*, p. 231.

[58]Pierce and Noll *op. cit.*, p. 198.

[59]Gerhard M. Sessler, "What's new in electroacoustic transducers" (*IEEE ASSP Magazine*, vol. 1 (1984), no. 4, pp. 3–11).

[60]Sessler *op. cit.*

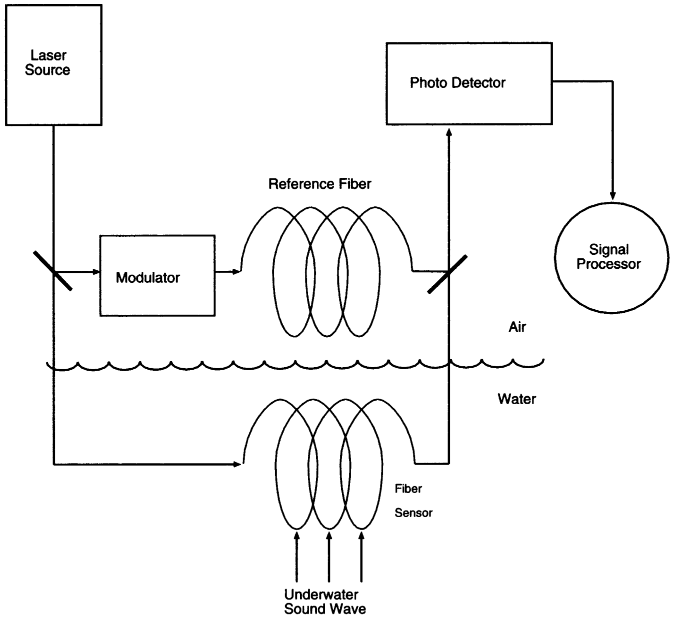

FIGURE 6. A fiber-optic interferometric sensor works by combining the light from a reference fiber and the light from fiber exposed to sound. Since the sound wave changes the phase of the light in the sensor fiber, the interference pattern of the recombined beam changes, allowing detection of the sound.[61] (Redrawn after figure on p. 3 of Gerhard M. Sessler, "What's new in electroacoustic transducers" (*IEEE ASSP Magazine*, vol. 1 (1984), no. 4, pp. 3–11).)

digital mixing consoles were available as early as 1984.[62] In 1983 the manufacturers of electronic musical instruments sanctioned a standard digital interface called MIDI (Musical Instrument Digital Interface);[63] MIDI allowed keyboards, synthesizers, and other electronic instruments to communicate with each other and with computers. By 1990 most synthesizers

[61]Sessler *op. cit.*

[62]Bloom *op. cit.* A technical advantage of digital audio, that a copy may be made that is identical to the original, has been seen as a disadvantage by the recording industry, since it makes piracy easier. Digital audio has special advantages with telephone answering machines, as messages may be easily stored, duplicated, annotated, and forwarded.

[63]*U.S. Consumer Electronics Industry Today* (Arlington, VA: Consumer Electronics Manufacturers Association, 1997), p. 60.

were fully digital, using microprocessors to manipulate the coded signal.[64] Synthesizers enable sound designers for cinema or stage to combine existing sounds and newly created sounds and to modify them in numerous ways (as changing tempo or adding or removing harmonics).[65]

In the 1980s the IEEE Acoustics, Speech, and Signal Processing Society continued its steady growth in membership, in publication, and in scope. The Society played a large role in the development of VLSI signal processing. There was, for example, an important workshop of this topic, organized by Sun Yuan Kung, in 1982.[66] Research, using techniques of graph theory, linear programming, and scheduling theory, was directed toward systematic procedures for the design of systolic arrays and regular iterative arrays.[67]

In 1983 the Society established a new technical committee on VLSI. Its concern was "the unique nature of VLSI technology as applied to signal processing, where the algorithm and its implementation strongly influence each other, and where the accumulation of algorithms available for implementation and the rapid evolution of new algorithms demand accelerated design techniques to rapidly develop VLSI-based systems for implementation."[68] The other five technical committees at that time were Digital Signal Processing, Speech Processing, Underwater Acoustics, Multidimensional Signal Processing, and Spectral Estimation. In 1972 *Transactions* began appearing six, rather than four, times a year, and in 1987 it began monthly publication. Toward the end of the decade the Society joined with several other IEEE Societies in the Neural Networks Council, which began publication of the *IEEE Transactions on Neural Networks* in 1990.

Over the past century many types of electrical technologies have become ubiquitous. For example, in the middle decades of this century, small

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[64]Frank E. Wukitsch and John Culbert, "Technology on stage" (*1991 Yearbook of Science and the Future* (Chicago: Encyclopaedia Britannica, 1990); pp. 200–223).

[65]Wukitsch and Culbert *op. cit.*

[66]Papers from that workshop became a book: Sun Yuan Kung, Harper J. Whitehouse, and Thomas Kailath, eds., *VLSI and Modern Signal Processing* (Englewood Cliffs, NJ: Prentice-Hall, 1985).

[67]See, for example, Sailesh K. Rao and Thomas Kailath, "Regular iterative algorithms and their implementation on processor arrays" (*Proceedings of the IEEE*, vol. 76 (1988), pp. 259–282).

[68]*IEEE ASSP Magazine*, vol. 1 (1984), no. 1, p. 32 (news item by John Ackenhusen).

electric motors made their way into tools, office equipment, home appliances, and vehicles, very often without people being aware of their presence. Similarly, in the 1980s microprocessors made their way into the store, the office, the living room, the kitchen, the laundry room, and the car. As we will see in the next chapter, signal processing was increasingly the reason for this innervating growth (some would say cancerous spread) of microelectronics.