Chapter 3

Halcyon Days for Audio Engineering: The 1950s

WHAT WAS HAPPENING IN THE 1950S

movies people were watching:
The African Queen with Humphrey Bogart and Katherine Hepburn
Ben-Hur with Charleton Heston
The Bridge on the River Kwai
Rebel Without a Cause with James Dean

TV shows people were watching:
"I Love Lucy"
"Dragnet"
"Leave It to Beaver"
Westerns: "Gunsmoke", "Have Gun, Will Travel", "Wagon Train", and many more

music people were listening to:
Leonard Bernstein's "West Side Story"
songs of Elvis Presley

books people were reading:
Norman Vincent Peale's *The Power of Positive Thinking*
Jack Kerouac's *On the Road*
J.D. Salinger's *The Catcher in the Rye*

Popular enthusiasm for higher quality sound made the 1950s an exciting time to be an audio engineer. Those concerned with disk recording made improvements associated with the new LPs and 45s, such as better recording, mastering, and processing techniques and a new lower-force pickup. Though accurate measurement of the features and performance of phonograph systems began in the 1920s, it was not until the mid 1950s that the industry adopted standardized tests of recording characteristics, making it easier for engineers to communicate and for listeners to judge the relative merits of different phonograph sets or components.[1] (Standardization of tests of radio-receiver performance had been achieved by the IRE in about 1930.)[2]

Experiments in the use of two or more microphones and two or more speakers to recreate "auditory perspective", the spatial distribution of sound, go back to a demonstration of 2-channel sound transmission at the Paris Electrical Exposition in 1884.[3] The 1930s saw the development of several systems for stereophonic phonograph recording, notably by Alan Blumlein

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[1]William S. Bachman, Benjamin B. Bauer, and Peter C. Goldmark, "Disk Recording and Reproduction" (*Proceedings of the IRE*, vol. 50 (1962), pp. 738–744).

[2]Frederik Nebeker, "The development in the 1920s of test-and-measurement techniques for the design of radio receivers" (*Wescon/92 Conference Record*, IEEE and ERA, Anaheim CA; 17–19 November 1992, pp. 802–807).

[3]Morton D. Fagen, ed., *A History of Engineering and Science in the Bell System: The Early Years (1875–1925)* (New York: Bell Telephone Laboratories, 1975), p. 68.

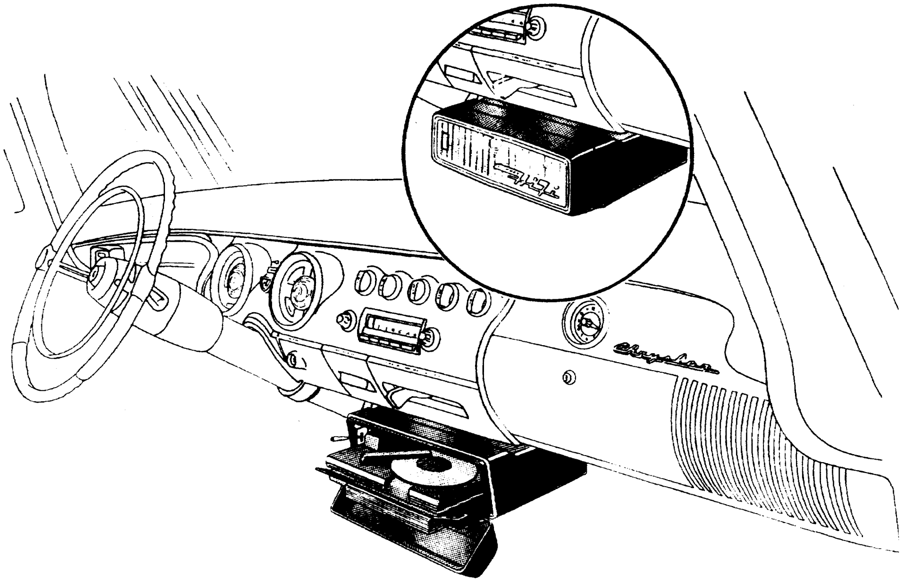

FIGURE 1. Three decades before car CD-players, the Goldmark car phonograph was available in all 1956 cars manufactured by the Chrysler Corporation. (Chrysler Corporation image reproduced by permission.)

in England and Arthur Keller in the U.S., but stereophonic recording did not then become a commercial product.[4] When stereo records were finally offered to the public in 1957, they became popular immediately.[5]

Two other areas of work by phonograph engineers in the 1950s were dictating machines and car phonographs. Phonograph recording for office dictation was a successful, and continually improved, technology from the late 19th century—Edison saw it as one of the most important uses of his invention—through the 1950s. Peter Goldmark and CBS Laboratories developed an automobile phonograph system in 1955 that was available in all 1956 Chrysler Corporation cars (see Figure 1).[6] There was, however, little

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[4]Stereo did come to movie theaters earlier: first in Paris in 1932 (for a sound version of Abel Gance's 1927 classic "Napoléon Bonaparte") and later to great popular acclaim with Walt Disney's "Fantasia" in 1941 [Ed Lyon, "Stereophonic sound—part 2" (*Radio Age*, vol. 20 (1995), no. 7, pp. 1–7)].

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

[6]Bachman, Bauer, and Goldmark *op. cit.*, and William E. Butterworth, *Hi-Fi: From Edison's Phonograph to Quadraphonic Sound* (New York: Four Winds Press, 1977), p. 166.

Leo Beranek: We found that the old methods of calibrating microphones that the Bell Labs were using were in need of change and new methods were developed. We were running the only real scientific airborne laboratory, in the world, I'd say it turned out. The rest of the world had shut these things down, were all doing underwater sound. That included Japan and Germany as well as England and France—France was probably taken over by the Germans by then.

This then led to another point. Remember, we were dealing now with things that really belong in the radio engineer's field. We were dealing with microphones and earphones and communication.

... My paper became the basis for the American National Standards that were written later on. My other major publication as a result of this war work [still available from the Acoustical Society of America] was my book *Acoustic Measurements*.[1]

Alfred Fettweis: We designed filters, but now in a somewhat higher frequency range, with the modern method. That's the task Belevitch gave me, and I had to fight with these numerical intricacies. It was very difficult, of course. It took me two months, from morning to night, calculating on an electromechanical desk-calculator to design the filter. Then I got assigned some young girl who had only attended grade school, and she then did the work for me. I had to divide up all the work into small steps which she could understand. She did not know what a zero of a polynomial equation would be, or anything like this. So I did something like what you do for programming a computer at that early stage.[2]

James Flanagan: [The MIT Acoustics Lab in the 1950s] was multidisciplinary with people from physics, mathematics, engineering, psychology and architecture. All these folks worked together in a very effective way. The primary thrust of the laboratory was physical acoustics and communications acoustics.[3]

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[1]Leo Beranek oral-history interview 22 November 1996, pp. 39–40.

[2]Alfred Fettweis oral-history interview 24 April 1997, p. 29.

[3]James Flanagan oral-history interview 8 April 1997, p. 7.

public interest, which Goldmark attributed to apathetic marketing by Columbia and Chrysler.[7] For this application, as with office dictation, a different technology—magnetic recording—came to the fore in the 1950s.

Magnetic recording, too, was part of the hi-fi movement. Ampex began to sell tape recorders in about 1948—these were, of course, reel-to-reel recorders—and went on to dominate the U.S. market. In 1954, when the difficulties of mass-producing them had been solved, pre-recorded tapes began to be sold, though they did not approach LPs in sales.[8] The 1950s was a period of intense work on understanding the physical processes underlying magnetic recording.[9]

Microphone design was another important area of audio engineering. Employing a wide range of transducers—carbon, condenser, piezoelectric, moving conductor, moving armature, and many others—engineers improved the performance of microphones and designed them for a great many specialized applications. In the 1950s two types that received much attention were directional microphones and wireless microphones.[10]

Continuing work on loudspeakers included efforts to achieve smoother frequency-response characteristics, more uniform directional patterns, lower nonlinear distortion, and superior response to transients.[11] In the 1950s and 1960s the design of loudspeaker enclosures was put on a firm theoretical foundation; Leo Beranek's *Acoustics*, published in 1954, was a landmark.[12] For public-address systems, there were new techniques to achieve desired directional patterns from individual loudspeakers and from loudspeaker arrays.[13]

There were other contributors to the hi-fi movement. One factor was the great interest in classical music, a musical taste often associated with

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[7]Peter Goldmark with Lee Edson, *Maverick Inventor: My Turbulent Years at CBS* (New York: Saturday Review Press, 1973), pp. 148–155.

[8]Roland Gelatt, *The Fabulous Phonograph: From Tin Foil to High Fidelity* (Philadelphia: J.P. Lippincott, 1954), p. 298.

[9]Marvin Camras, "Current problems in magnetic recording" (*Proceedings of the IRE*, vol. 50 (1962), pp. 751–761).

[10]Benjamin B. Bauer, "A century of microphones" (*Proceedings of the IRE*, vol. 50 (1962), pp. 719–729).

[11]Harry G. Olson, "Loudspeakers" (*Proceedings of the IRE*, vol. 50 (1962), pp. 730–737).

[12]Leo Beranek, *Acoustics* (New York: McGraw-Hill, 1954), and Kahrs *op. cit*.

[13]Winston E. Kock, "Speech communication systems" (*Proceedings of the IRE*, vol. 50 (1962), pp. 769–776).

concern for high fidelity.[14] A second factor, unnoticed by most consumers, was the availability of accurate test equipment. This equipment allowed engineers to set standards of performance for the various parts of electroacoustic systems, so that components could be combined to achieve predictable performance.[15] Another factor was a vigorous group of entrepreneurs—Amar Bose, Avery Fisher, Sidney Harman, Jim Lansing, Saul Marantz, Hermon Scott, and many others—whose technologically superior products stimulated demand.[16]

Among the new products was FM radio, which had begun just before the war. It gave not only higher fidelity music, but also reception that was almost free from static.[17] The eventual acceptance of FM owed much to theoretical work in loudspeaker design. Edward Howard Armstrong, the principal developer of FM radio, had been promoting it for more than a decade with only moderate success when in about 1950 he consulted with Leo Beranek and Jerome Wiesner at MIT. Beranek and Wiesner analyzed the problem as one of cost and size of equipment: besides an FM receiver, the listener needed an amplifier and a large loudspeaker cabinet to get hi-fi quality. Beranek devised an analog circuit that modeled all parts of a loudspeaker, including the electrical circuit, the transducer, the radiating cone, and the air into which the sound passed. Edgar Villchur of the AR loudspeaker company used the Beranek theory to design a small hi-fi loudspeaker that could be inexpensively manufactured, and it contributed to the success of FM in the 1950s.[18]

The 1950s are often portrayed as a tranquil period in U.S. history. The economy was growing steadily, most U.S. voters were quite content with Dwight Eisenhower as President (1953–1961), and there was political stability—at least in comparison to the troubled 1940s—in most of the world. People were spending more time at home. It was a do-it-yourself age

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[14]In the U.S. in 1954, $70 million was spent on recordings of classical music, whereas 20 years earlier perhaps $750,000 was [Gelatt *op. cit.*, p. 302].

[15]Oliver Read and Walter L. Welch, *From Tin Foil to Stereo: Evolution of the Phonograph* (Indianapolis, IN: Howard W. Sams, 1959), p. 350. A landmark in the science of acoustic measurement was Leo Beranek's *Acoustic Measurements* (New York: John Wiley & Sons, 1949).

[16]*U.S. Consumer Electronics Industry Today* (Arlington, VA: Consumer Electronics Manufacturers Association, 1997), p. 84.

[17]In the early 1950s the National Association of Radio and Television Broadcasters promoted the slogan "In radio, there is no high fidelity except in FM transmission" [*Newsweek*, 21 December 1953, p. 69].

[18]Leo Beranek personal communication 2 January 1998.

and the decade most Americans discovered the backyard barbecue. Television had rapidly become a major part of American life: in 1957 85 percent of homes had a television set, which was watched an average of five hours a day.[19] In Europe, too, the economy was growing (led by West Germany's "economic miracle"), and Western Europe took a step toward unity in 1957 when six nations signed the Treaty of Rome aimed at a common market.[20]

The tranquillity was, however, frequently disturbed. There were continuing conflicts between the Western powers and the Communist countries, notably the Korean War, which reached an uneasy truce in 1953, and the Soviet suppression of the 1956 Hungarian revolt. Americans received a psychological shock when the Soviets placed a satellite into orbit on 4 October 1957, a date that may be taken as the beginning of the Space Age. The tranquillity was disturbed also by rock music—Elvis Presley burst into stardom in 1956—and the transistor radio.

In 1954 the Regency Company, using components made by Texas Instruments, manufactured the first transistor radio. Though pocket-sized, its performance was poor and its price was high ($49.95).[21] In 1957 Sony (which until that year bore the name Tokyo Telecommunications Engineering Company) introduced a transistor radio (the TR-63) that set a new standard and attracted dozens of imitators. Soon, helped by the proliferation of all-rock radio stations, transistor radios became an essential part of the youth culture. Sony's transistor radios also helped establish a market for personal electronics, devices meant for a single user.[22]

At about the same time as the introduction of the transistor radio came the celebration of the first transatlantic telephone cable. (See Figure 2.) Though telegraph cables across the Atlantic date back to 1858, the necessity for telephony of using repeaters (that is, amplifiers) and the difficulty in designing ones that would work under water for a long period of

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[19]Erik Barnouw, *Tube of Plenty: The Evolution of American Television* (second revised edition) (New York: Oxford University Press, 1990), p. 198.

[20]In 1950 the Germany economy was just beginning to recover from the devastation of the war; by 1960 it accounted for one-fifth of the world trade in manufactured goods and had surpassed the British economy [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).]

[21]Michael Brian Schiffer, *The Portable Radio in American Life* (Tucson, AZ: University of Arizona Press, 1991), pp. 176–178.

[22]Schiffer *op. cit.*, pp. 206–211.

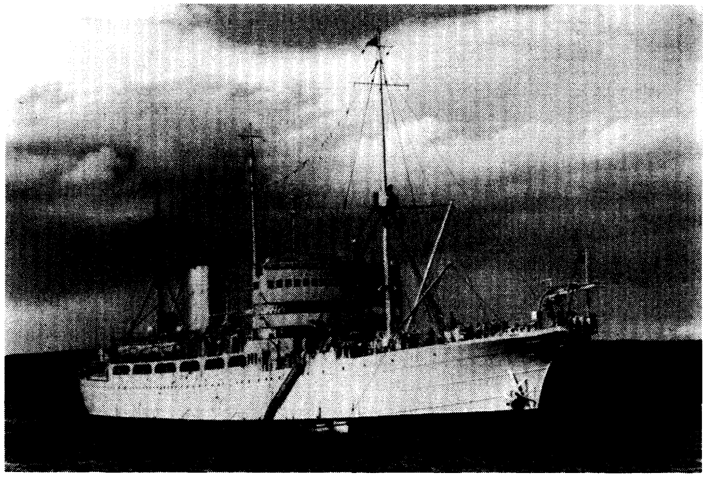

FIGURE 2. The transatlantic telephone cable, laid by ship as shown, was put into operation in 1956. (Bell Labs photo reproduced by permission.)

time meant that until 1956 the only way to transmit a telephone signal from the United States to Europe was by radio.[23]

The 51 deep-sea repeaters in the transatlantic cable used electron tubes, since at the time appropriate transistors of established reliability were not available. For sheathing and insulation the cable made use of new synthetic materials, such as polyethylene. Two cables were actually laid, each carrying signals in a single direction, as this allowed a simpler design for the repeaters. Together the cables carried 64 bidirectional voice channels.[24]

So valuable were the undersea telephone channels that engineers devised a system, called time assignment speech interpolation (TASI), to take advantage of the pauses in speech during a telephone conversation. A per-

[23]AT&T began operating a transatlantic radiotelephone service in 1927, but static and ionospheric disturbances degraded voice-quality and sometimes interrupted service [Eugene F. O'Neill, ed., *A History of Engineering and Science in the Bell System: Transmission Technology (1925–1975)* (New York: AT&T Bell Telephone Laboratories, 1985), p. 337].

[24]O'Neill *op. cit.*, pp. 341–345. A common misconception, which even appears in print (e.g. Frank N. Magill, ed., *Great Events from History II* (Pasadena CA: Salem Press, 1991), pp. 1502–1507), is that transistors made possible the transatlantic telephone cable. The electron-tube repeaters of the 1956 cable all exceeded the 20-year expected life; there had been no electronic failures when the system was taken out of service in 1979 [O'Neill *op. cit.*, p. 345]. The fifth transatlantic telephone cable, which was completed in 1970, was the first to use transistors rather than tubes [*Britannica Yearbook of Science and the Future 1971* (Chicago: Encyclopaedia Britannica, 1970), p. 165].

James Flanagan: My thesis was on an automatic formant tracker which involved building a real-time spectrum analyzer. This was essentially a custom designed filter bank to do the spectrum analysis, an electromechanical scanner that would convert the spectral envelope into signals that could be analyzed, and then an electronic logic set that would attempt to identify the resonant peaks in that spectrum. Part of the thesis was then to evaluate how well that formant tracker did and how well one could synthesize speech from that information.

Interviewer: Was this actually built?

Flanagan: Yes, over about a 3-year period. It ended up being all vacuum tubes. This was before integrated circuits obviously, even before transistors. It must have been about four, or maybe five, 6-foot relay racks of electronic equipment, with lots of heat generated.[1]

Interviewer: You said you started to drift into speech. Can you tell me about how that happened?

Ben Gold: Yes, I was interested in problems of this sort. I was 16 when I went to see the New York World's Fair. At the fair they had an exhibit of the Voder. It was fascinating. Here was a machine that kind of spoke. Not very well, but it spoke. I was more interested in some of the other things. There was an exhibit where if you won a lottery you could make a long distance call to anybody in the country through the Bell System, and everyone could listen in. I got a real kick out of that, but that didn't lead to anything later. The Voder, on the other hand, I always remembered.[2]

[1]James Flanagan oral-history interview 8 April 1997, pp. 4–5.

[2]Ben Gold oral-history interview 15 March 1997, p. 4.

son using the telephone talks, on average, less than 40 percent of the time. TASI, using speech detectors and fast electronic switches, could transmit parts of other telephone conversations during the pauses. A signaling and switching system at the receiving end ensured that a listener is always connected to the correct line. Put into service in 1960, TASI doubled the capacity of the cable and may be the first example of a commercial time-division switch.[25]

[25]Kock *op. cit.*, and O'Neill *op. cit.*, pp. 348–349.

The telephone cable was an important step toward a worldwide network for instantaneous voice communication. Ironically, after the long wait for undersea telephony, it was soon challenged. In 1962 AT&T placed the first commercial communications satellite, Telstar, into orbit. With ground stations in the U.S., France, and Britain, the satellite system could carry 600 telephone calls or one television channel.[26] There soon followed the Communications Satellite Corporation (COMSAT), the International Telecommunications Satellite Consortium (INTELSAT), and several series of communications satellites.

Efforts to increase the capacity of a communication channel have a long history: the first duplex telegraphs, able to send two signals simultaneously on the same wire, were invented in the 1850s, and Alexander Graham Bell's first interest in electrical communication was his scheme for multiplex telegraphy, sending signals at different frequencies on the same wire.[27] Data compression, too, goes back to the early decades of telegraphy, with code books that allowed businesses to compress whole sentences to single words.[28]

For the telephone companies the most important way of increasing transmission capacity was the introduction of carrier telephony, or frequency-division multiplexing, which allowed many telephone signals to be sent over the same line, each within a particular bandwidth.[29] The technique made heavy use of electron tubes, as oscillators, modulators, demodulators, and amplifiers. Also vital were wave filters, that is, circuits that passed only the frequencies within a specified range.[30] Since these methods

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[26]O'Neill *op. cit.*, pp. 377–394. In Telstar there were some 6000 transistors and only one vacuum tube (a traveling-wave tube used as an amplifier). The first conversation over Telstar was less memorable than Samuel Morse's "What hath God wrought?" or Alexander Graham Bell's "Mr. Watson, come here. I want you": AT&T Chairman Frederick Kappel in Andover, Maine asked Vice President Lyndon Johnson in Washington "How do you hear me?", to which Johnson replied "You're coming through nicely" [*Communications* (a volume of the series Understanding Computers) (Alexandria, VA: Time-Life Books, 1986), pp. 79–80].

[27]W.A. Atherton, *From Compass to Computer: A History of Electrical and Electronics Engineering* (San Francisco: San Francisco Press, 1984), pp. 98–100.

[28]Jim Reeds, "Data compression—for telegraph" (*Antenna*, vol. 9 (1997), no. 2, p. 10). Reeds gives two examples from *Harvey's Mining Code* (1889), one of many trade-specific code books: 'convicteth' meant 'Old shaft will need retimbering' and 'archons' meant 'Send two good Cornish miners'.

[29]A voice signal occupies a bandwidth of about 4000 Hz, and this signal may be shifted to another position in the frequency spectrum for transmission and shifted back to the audio range before it reaches the receiver.

[30]Morton D. Fagen, ed., *A History of Engineering and Science in the Bell System: The Early Years (1875–1925)* (New York: Bell Telephone Laboratories, 1975), pp. 279–280.

Ben Gold: ... One day in late 1959 or early 1960, I found myself at Bell Labs talking to a gentleman named John Kelly, who is now gone [he died in 1965], and he was describing something called the Pitch Detector to me, and he talked about vocoders. I had heard of vocoders, but I hadn't been very aware of what it was all about. And Kelly inspired me to look very carefully at the problem of finding the fundamental frequency of human speech.

I was at Lincoln at that time, I had already built the Morse Code Translator, and I came back and started working on this pitch problem. That was my entry into signal processing. I did it just out of curiosity. In those days at Lincoln Lab you could almost pick and choose what you wanted to work on, up to a certain point. Working on pitch detection was considered okay, but my boss wanted to turn it into something "useful".

Interviewer: Who was that?

Gold: A fellow named Paul Rosen. What he said was, "Well, if you have such a good pitch detector, shouldn't we build a vocoder that includes that pitch detector?" So that put me onto vocoders. Now, a vocoder, among other things, has many filters in it, and once you get into filters you are into signal processing. It was frustrating at the beginning because although the computer was capable of doing a good program for pitch detection, it really wasn't capable of simulating an entire vocoder. It was just too complicated. Nobody knew how to do filters on computers. So we were in a way poised when we realized that, "Hey, maybe there's a way to do this." We got very, very excited, and we started doing a lot of work very quickly over a period of maybe two or three years, and that's where most of the work came from.[1]

[1]Ben Gold oral-history interview 15 March 1997, p. 3.

were standard in radio engineering, carrier telephony illustrates a general historical trend toward convergence of techniques of wire and wireless communications.[31]

Karl Willy Wagner in Germany and George A. Campbell in the United States helped establish a theory of wave filters.[32] The subject received great impetus from the work of Wilhelm Cauer, Sidney Darlington,

[31]Ivan S. Coggeshall, "The compatible technologies of wire and radio" (*Proceedings of the IRE*, vol. 50 (1962), pp. 892–896).

[32]Pioneer publications were Karl Willy Wagner's "Spulen- und Kondensatorleitungen" (*Archiv für Elektrotechnik*, vol. 3 (1915), pp. 315–322) and George A. Campbell's "Physical theory of the electrical wave filters" (*Bell System Technical Journal*, vol. 1 (1922), pp. 1–32). Others who made important early contributions to filter theory were R.M. Foster and O. Brune.

ENDERS ROBINSON: So Professor Hurley obtained eight seismic records, like this one, so that I actually had the data in the fall of 1950.... The first step was for me to hand-digitize these eight records by putting a T-square down with a scale and reading off the traces point-by-point, putting them in numerical form.

INTERVIEWER: You probably had a pretty modest sample rate!

ROBINSON: Yes ... it took a couple of days to do a record. And then you'd have to check to make sure.[1]

ENDERS ROBINSON: To get back to 1951, we had a method that worked, which was called deconvolution. The next question was how to compute it. It took all summer to deconvolve a few of these traces with Virginia Woodward [working with a Marchant desk calculator]. At that time MIT had a computer they called Whirlwind.... Like the ENIAC, it took whole rooms, a whole building, the Barta Building at MIT.... So in the spring of 1952 I went to Whirlwind with Howard Briscoe and put deconvolution on Whirlwind.[2]

[1]Enders Robinson oral-history interview 6 March 1997, p. 6.

[2]Enders Robinson oral-history interview 6 March 1997, p. 10.

and others. Cauer's 1926 dissertation on *The Realization of Impedances of Specified Frequency Dependence* was a landmark contribution to the systematic understanding of electrical filters. Cauer stated clearly the objective of being able to design a filter having prescribed characteristics: "... it is less important for the electrical engineer to solve given differential equations than to search for systems of differential equations (circuits) whose solutions have a desired property."[33]

AT&T introduced carrier systems as early as 1918 and 1920, but the first system to be widely adopted was introduced in 1924. On a single pair of wires, three 2-way voice channels were carried at frequencies above the voice frequencies (in the 5 to 30 kHz range), thus quadrupling capacity.[34] Continued improvements to carrier systems were made possible by the negative-feedback amplifier and by new electron tubes for use with higher frequencies (to 100 MHz and above).[35] Coaxial cable, with much greater

[33]Emil Cauer and Wolfgang Mathis, "Wilhelm Cauer (1900–1945)" (*Archiv für Elektronik und Übertragungstechnik*, vol. 49 (1995), pp. 243–251); the quotation is from p. 244.

[34]O'Neill *op. cit.*, pp. 5–6.

[35]O'Neill *op. cit.*, p. 2.

Enders Robinson: The water layer itself is reverberating like a drumhead and that hid the signals coming from the depths. Deconvolution removed those reverberations.

By the late 1950s there were lots of areas they wanted to explore offshore, like the Gulf of Mexico and the Persian Gulf, and in Venezuela they had Lake Maracaibo. They realized that the only way they could get rid of water reverberations was by deconvolution. The only way they could deconvolve was by signal processing, because analog cannot do it. So they were sort of forced into digital that way.

... The analog methods they used would be electrical band-pass filtering, high-pass filtering, and low-pass filtering. They could also adjust the traces in time: move one trace with respect to the other. In other words, they might think, "Well, the signal's coming in at 40 hertz, so we will band-pass it close to 40 hertz to find the signal." That would be analog processing because they did it by an electric circuit.

Interviewer: And that was supposed to strip out the reverberations?

Robinson: They could use band-pass filtering if the reverberations were at a different frequency than the deep reflections. That was the idea, but it didn't work because all these signals overlapped in frequency. The companies decided they had to get rid of those reverberations, which they could do through deconvolution. That meant going digital, so they started spending the money. That was the advantage of the oil industry, they had money. The other thing is that they had a history of spending money on computers through their refining operations. They had close contacts with IBM and other computer companies.[1]

[1] Enders Robinson oral-history interview 6 March 1997, p. 18.

bandwidth, and, in the 1950s, microwave relay systems permitted carrier systems of higher capacity, such as the L-3 system bearing 1800 voice channels in one circuit.[36]

A different approach to increasing transmission capacity was that taken by Homer Dudley at Bell Labs in the 1930s. He reasoned that speech is formed by modulating, with slowly changing vocal resonances, the sound produced by vocal sources, either the vocal cords or the turbulent airflow at constrictions in the vocal tract. The source could be characterized as either aperiodic (unvoiced sounds) or periodic (voiced sounds), and if it is periodic its frequency could be measured. The modulations of the speech spec-

[36] Kock *op. cit.*

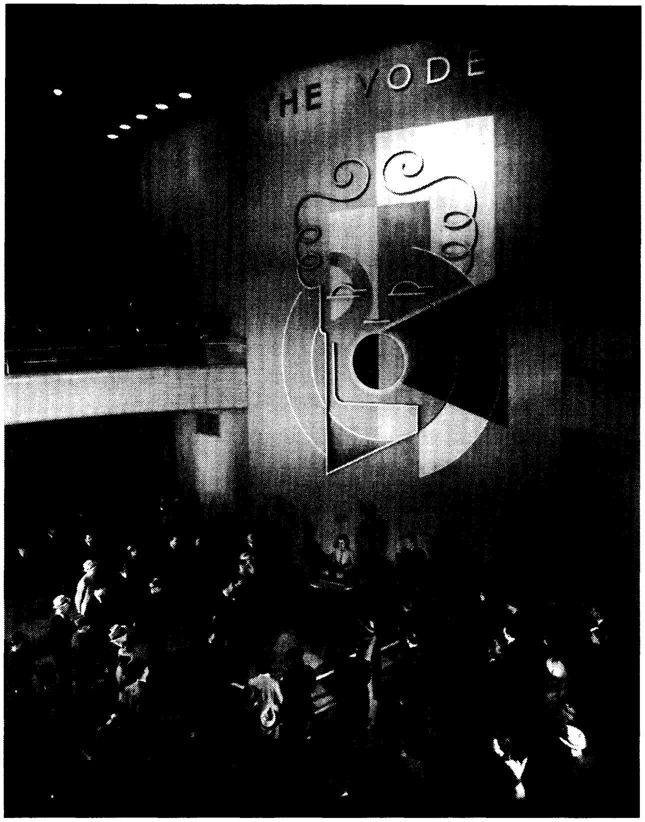

FIGURE 3. Speech-processing technology had never before been as glamorous as it was at the 1939 New York World's Fair, where the Voder, a speech synthesizer, was demonstrated. The operator worked at a keyboard, with a wrist bar to control the voicing parameter and a pedal for pitch control. (Bell Labs photo reproduced by permission.)

trum could be measured by the relative energy in contiguous filter bands. This information might then be transmitted and the speech reconstituted at the receiver. The analysis-synthesis system, called the "vocoder", could achieve speech transmission with a 300-Hz bandwidth, while a traditional telephone channel required a bandwidth of 3000 Hz.[37] The so-called "Voder" used hardware conceptually similar to the vocoder synthesizer, but the Voder was a human-controlled synthesizer. (See Figure 3.)

[37]Sidney Millman, ed., *A History of Engineering and Science in the Bell System: Communication Sciences (1925–1980)* (AT&T Bell Telephone Laboratories, 1984), pp. 99–102; and Ben Gold personal communication 30 January 1998.

Interviewer: Can you re-cap the transition from when people were skeptical to when the companies started investing in it?

Enders Robinson: It came when Texas Instruments Company, which was Geophysical Services Incorporated, said, "give us your exploration records from the Gulf of Mexico and we'll remove the reverberation by deconvolution." Then they showed the results, and everybody flip-flopped.

Interviewer: And that happened in the late 1950s?

Robinson: Early 1960s. They were working on it in the late 1950s. The geophysical people involved at Texas Instruments were previously my research assistants at MIT. Mark Smith was one who was really working on this; he became vice-president at Texas Instruments. Cecil Green was so ecstatic he gave MIT a building—the Green Building—which was his first real act of philanthropy, and from there he gave professorships and more buildings to several universities.

Interviewer: You're saying that Texas Instruments led the way, then other exploration companies developed that ability too?

Robinson: It is fair to say that of all the geophysical companies, Texas Instruments had the ability and motivation to carry out this program.[1]

Manfred Schroeder: ... In early June 1954, I got a letter from Bell Labs offering me a job at $640 per month. I could have gone to Siemens for 500 marks a month, but here was a better company offering me five times as much, so of course I accepted. I would have gone for nothing.[2]

Manfred Schroeder: I thought I should do something of fundamental interest to Bell Laboratories, and I elected on my very first day at Bell Labs to go into speech. I felt this should be of interest to the telephone system, and it was something new.

So I started speech research. After two years or so I discovered I couldn't really make my speech synthesizers sound better if I didn't know more about the human ear, so I got into hearing research. Then quite a few years later we were starting to think about speakerphones and conference telephone arrangements. Then room acoustics came in again. So the main parts of my career at Bell Labs dealt with speech, hearing, and room acoustics, in that temporal order.[3]

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[1]Enders Robinson oral-history interview 6 March 1997, p. 24.

[2]Manfred Schroeder oral-history interview 2 August 1994, p. 40.

[3]Manfred Schroeder oral-history interview 2 August 1994, p. 46.

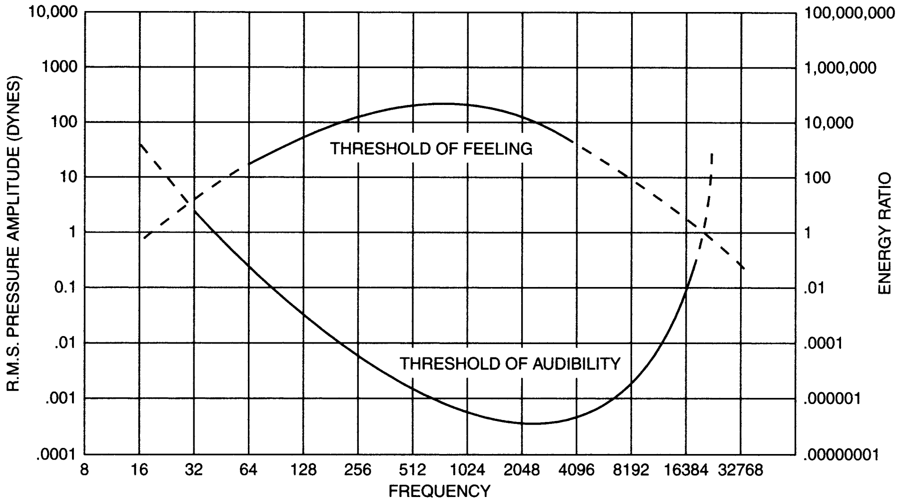

FIGURE 4. The range of human audition as depicted by Harvey Fletcher and Raymond L. Wegel in 1927. The vertical axis is pressure amplitude; the horizontal axis is frequency. (Bell Labs image reproduced by permission.)

Dudley's work provides one example of the research on human speech and hearing conducted, over more than 70 years, at Bell Telephone Laboratories in order better to design telephone equipment that faithfully, or at least intelligibly, conveys the human voice.[38] An earlier example is the graphical depiction of the range of human hearing published in 1927 by Harvey Fletcher and Raymond L. Wegel; it has become one of the landmarks of 20th-century science. (See Figure 4.) In conducting such research, engineers developed the new electronic tools of audio engineering, such as oscillators, amplifiers, attenuators, and frequency analyzers.

In the 1940s Ralph K. Potter and other researchers at Bell Labs began producing sound spectrograms, which are portrayals of the frequency content of speech as it varies with time.[39] The sound spectrograph, the machine that produces the spectrograms, is an early example of signal-processing hardware. (See Figure 5.) It became standard in phonetics laboratories around the world.[40] Figure 6 shows a spectrogram with some of the characteristics of the speech marked. This display format for speech continues to

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[38]Fagen *op. cit.*, pp. 926–958.

[39]Fagen *op. cit.*, p. 957.

[40]Millman *op. cit.*, pp. 104–106.

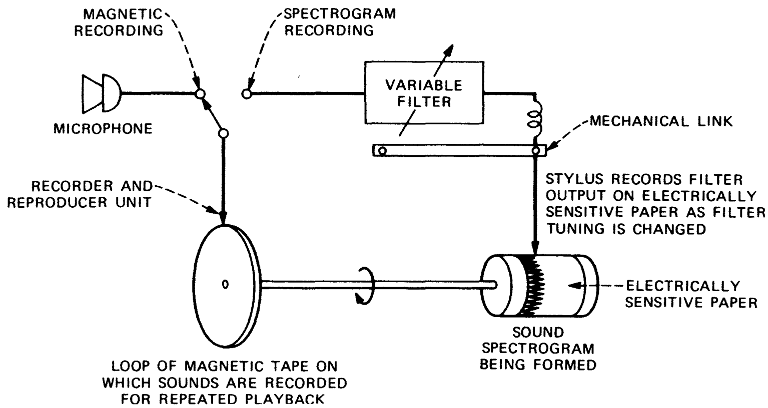

FIGURE 5. This diagram shows how the spectrograph works. (Audio Engineering Society image reproduced by permission.)

be used today.[41] And the technique itself—time-frequency signal representation—came to be widely used in signal processing.[42]

One approach to understanding human speech and hearing was by simulation, and in 1950 Bell Labs researchers constructed electrical analogs of the vocal tract and of the inner ear.[43] In a few fields, such as meteorology, numerical simulation had been tried, but the technique was little known and would in most cases, since computers were not available, have been impractical.[44]

Understanding of human speech was employed to devise more effective means of transmission. For example, the late 1950s saw pioneering work, both at Bell Labs and at MIT's Lincoln Laboratory, on automatic recognition of phonemes (speech sounds). This had many potential applications, one being even greater bandwidth compression than the vocoder,

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[41]Robert W. Lucky, *Silicon Dreams: Information, Man, and Machine* (New York: St. Martin's Press, 1989), p. 226. A landmark book published in 1947, *Visible Speech* by Ralph K. Potter, George A. Kopp, and Harriet C. Green, made this technique widely known [Lucky *op. cit.*, p. 226].

[42]Franz Hlawatsch and G. Faye Boudreaux-Bartels, "Linear and quadratic time-frequency signal representations" (*IEEE Signal Processing Magazine*, vol. 9 (1992), no. 2, pp. 21–67).

[43]Millman *op. cit.*, pp. 106–107.

[44]Frederik Nebeker, *Calculating the Weather: Meteorology in the 20th Century* (New York: Academic Press, 1995), pp. 107–110. One of the first extensive uses of numerical simulation in engineering was in the Manhattan Project to build the atomic bomb, but this work was of course not publicized.

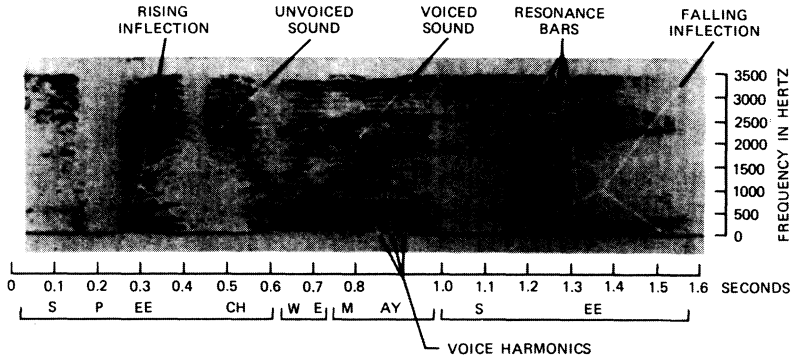

FIGURE 6. In the spectrogram the horizontal axis is time, the vertical axis is frequency, and the intensity of the sound is shown by the darkness. (Bell Labs photo reproduced by permission.)

since all that would need to be transmitted is the indication of what phonemes make up an utterance.[45]

In the improvement of communications, as well as the audio technologies discussed earlier, electroacoustics played an important part. Electroacoustics is the technology of converting acoustic energy into electric energy and vice versa. A technology comprises a set of techniques and the scientific understanding of them. Though there were earlier examples of electroacoustic transducers (devices that convert energy from one form into another), such as electric bells and telegraph sounders, it was Alexander Graham Bell's invention of the telephone in 1876 that made electroacoustics a major field of endeavor.[46] The development of electron tubes in the first decades of the 20th century enlarged the field, as it led to new applications of microphones, loudspeakers, and other types of electroacoustic transducers in radio, public-address systems, the electric phonograph, sound movies, magnetic recording, and underwater sound-ranging (later known as sonar). Here we see the electron tube as an enabling technology that, like the integrated circuit later, allowed a great expansion of the realm of signal processing.[47]

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[45]Kock *op. cit.*, and Eva C. Freeman, ed., *MIT Lincoln Laboratory: Technology in the National Interest* (Lexington, MA: MIT Lincoln Laboratory, 1995), p. 231.

[46]An excellent history of electroacoustics, which takes the story up to the 1930s, is in Frederick V. Hunt's *Electroacoustics: The Analysis of Transduction, and Its Historical Background* (Cambridge, MA: Harvard University Press, 1954).

[47]Gerald Tyne's *Saga of the Vacuum Tube* (Indianapolis, IN: Howard W. Sams, 1977) describes the development and manufacturing of electron tubes up to 1930.

Manfred Schroeder: One early highlight was the following: The main problem with synthesizing not just intelligible speech, which we could do, but natural sounding speech was the so-called pitch problem, extracting the fundamental frequency from telephone quality—pardon the expression—speech signal. In about 1955 John Pierce asked me to use Homer Dudley's vocoder principle, not to compress the bandwidths of telephone speech so you could send five times as many conversations over a transatlantic cable, but to take a high-fidelity speech signal off a bandwidth of 10 kilohertz or more, compress that down to 3 kilohertz, and send it over regular telephone channels. In other words, send high quality speech over regular telephone channels. That was what John Pierce asked of me. His idea was another application of Dudley's vocoder.

I said, "John, we want to send something that's even better than telephone speech, and we have this pitch problem. How can we ever get something better if we can't solve the pitch problem?" Well, it was quite clear it couldn't be solved. So my idea was to take a so-called baseband speech signal up to 2 kilohertz, then synthesize the rest from 2 kilohertz to 10 kilohertz by Dudley's vocoder method, and circumvent the pitch problem by generating the higher harmonics from applying a very severe nonlinear distortion to the baseband.

So you transmit the baseband from 300 to 2000 hertz. At the other end you would take the baseband, distort it nonlinearly to generate frequencies up to 10 kilohertz, and then vocoder-fashion give them the right amplitude. This thing was christened "voice-excited vocoder" by Ed David. (David later became Science Advisor to the President with an office in the White House.)

Everybody was flabbergasted. Pierce said, "Manfred, that's the first recorder that sounds like a human!" Yes, because it had the natural intonation. What makes human speech sound so natural is the intonation pattern and not the buzzy kind of synthetic speech that you usually hear. That was a real breakthrough, and so shortly after that I was put in charge of all acoustics research.[1]

[1]Manfred Schroeder oral-history interview 2 August 1994, pp. 55–56.

A science of electroacoustics requires the ability to measure the performance of transducers, amplifiers, and filters, both steady-state and transient response. A basic tool, the sound-level meter, was improved in the 1950s through the use of transistors and rugged condenser-microphones. Engineers specified protocols for measuring the characteristics of microphones and loudspeakers, such as directivity vs. frequency, linearity vs. level, and power-available efficiency vs. frequency.[48] A valuable application

[48]Leo L. Beranek, "Electroacoustic measuring instruments and techniques" (*Proceedings of the IRE*, vol. 50 (1962), pp. 762–768).

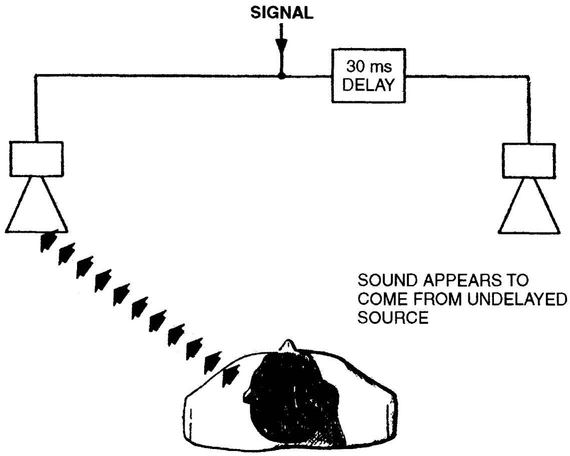

FIGURE 7. A modern version of the Buridan's-ass problem is solved by signal delay: if the same sound comes from two sources, the hearer perceives the sound as coming from the source with least delay. (IEEE image reproduced by permission.)

of electroacoustic transduction was the electronic artificial larynx developed in 1959 at Bell Labs and marketed by Western Electric; when pressed against the throat it supplied sound similar to that of the vocal cords.[49]

Electroacoustics is closely allied to the study of human speech and hearing, since such study frequently leads to improved design of electroacoustic devices. For example, in 1951 Helmut Haas discovered that if the same sound comes from two sources, and if the signal from the one is delayed 5 to 35 milliseconds, then the hearer perceives the sound as coming from the undelayed source even if it is many decibels weaker. (See Figure 7.) Shortly after its discovery, this so-called Haas effect was used in designing the public-address system for St. Paul's Cathedral in London. (See Figure 8.)

Also related to electroacoustics are underwater acoustics and the design of sonar systems. In the first world war, hydrophones, or underwater microphones, were much used as a means of detecting submarines.[50] To determine the direction of a sound, arrays of hydrophones were used, and they were steered either mechanically (repositioning the array) or—an early example of beamforming—electrically (using electrical compensators to introduce delays in the different hydrophone channels).[51] Some hydrophones

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[49]Millman *op. cit.*, p. 127.

[50]Willem D. Hackmann, *Seek & Strike: Sonar, Anti-Submarine Warfare and the Royal Navy 1914–54* (London: Her Majesty's Stationery Office, 1984), pp. 45–71.

[51]William S. Burdic, *Underwater Acoustic Signal Analysis* (Englewood Cliffs, NJ: Prentice-Hall, 1984), p. 8.

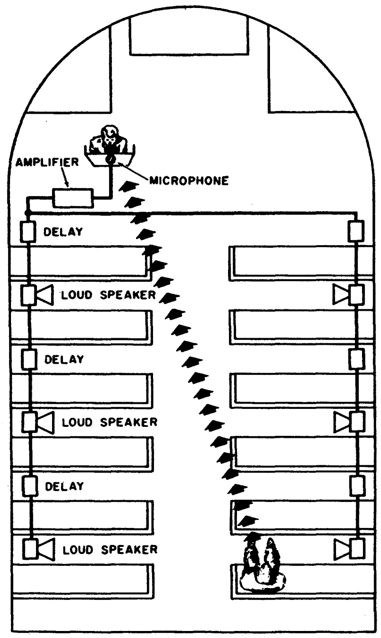

FIGURE 8. A public address system that incorporates delays in the lines to loudspeakers can give the audience the impression that the sound is coming directly from the human speaker. (As so often, the worshippers tend to sit at the back of the church: "If there were enough back pews, they could fill the church.") (IEEE image reproduced by permission.)

were equipped with electrical filters to improve the signal-to-noise ratio.[52] The early systems were analog, but in 1960 V.C. Anderson showed how to steer a hydrophone array using digital shift registers to introduce the desired delays.[53]

Radar was another area where digital signal processing was used in this period. One U.S. radar system, known as SAGE (Semi-Automatic Ground Environment), developed in the 1950s, did much to stimulate the development of both computer and communications technologies.[54] When completed in 1963, SAGE consisted of 23 interconnected direction centers,

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[52]Burdic *op. cit.*, p. 9.

[53]Burdic *op. cit.*, p. 13.

[54]The MIT computer project known as Whirlwind, headed by Jay Forrester, became part of the SAGE project. Among the innovations of Whirlwind was magnetic-core memory. For SAGE, IBM transformed the prototype Whirlwind into the IBM AN/FSQ-7 computer. Another innovation for SAGE was the cathode-ray-tube computer terminal. [Martin Campbell-Kelly and William Aspray, *Computer: A History of the Information Machine* (New York: Basic Books, 1996), pp. 165–169.]

HANS SCHUESSLER: The structures that you use for simulating transfer functions on an analog computer are precisely the same as you use for digital signal processing. The difference is that in the case of an analog computer you have just an integrator as the basic element. In DSP you have the delay element. In addition you need multipliers. In an analog case it's just a potentiometer; in the other case, it is a multiplier, a digital multiplier. The summation is done just with the integrated circuit—the integrator—it can be done easily: the structure is just the same. All the structures we have, we know for example the cascade structures, things like that, can be done and have been done, and I did it, back in the late '50s with analog means.

... [I used] the analog computer just to play with the potentiometers, shifting the poles and zeros around and looking at the impulse responses; and we found finally, as a hypothesis, that the minimum will be achieved if the frequency response in the stopband is of Chebyshev behavior, and the impulse response in the time domain dies out in a Chebyshev way as well. Somewhat like this.

INTERVIEWER: Empirically determined?

SCHUESSLER: Empirically. We could not prove it, but we found very good results just by playing with the analog computer. Again this hypothesis—not more—was a starting point for designing filters of this type on the digital computer.

INTERVIEWER: Why did you move to a digital computer?

SCHUESSLER: Well, finding let's say hundreds of examples just by playing around is one possibility, but it's not satisfying. In this case we have just the general rule, and developing the program to do that under certain constraints is by far better. And later on we have been told that these circuits—we published the results—have been really used in practice, which is somehow satisfying. By the way, a report about that has been published in the *IEEE Transactions on Circuit Theory*—that's '65.[1]

[1]Hans Wilhelm Schuessler oral-history interview 21 April 1997, pp. 5–7.

each fed by the radar data from some hundred stations. All together there were 1.5 million miles of communications lines, and data were transferred in digital form. For this purpose, MIT and Bell Labs engineers developed the first high-speed modems (modulator-demodulators for sending digital signals over the analog telephone-lines), which were capable of transmitting 1600 bits per second.[55] Related to the work on SAGE was the introduction in 1958 by AT&T of the Dataphone system, the first commercial modems specifically for transmitting computer data over phone lines.[56]

Radar and digital signal processing allowed President Eisenhower to claim a success for the United States in space exploration in the aftermath

[55]*Communications op. cit.*, p. 18.

[56]*Communications op. cit.*, p. 18.

of the Sputnik launch. This was the precise measurement of the distance of the moon by Lincoln Lab engineers. They used continuous-wave radar with pseudo-random pulse sequences, and then cross-correlated the reflected signals with the transmitted sequence. The signals were quantized to eight bits and recorded on tape. The cross-correlation peak indicated the travel time of the radar waves to the moon and back.[57]

Both sonar and radar involve processing weak signals in the presence of considerable noise, a challenge that occurs in many other areas as well, such as biomedical imaging and space communications. During World War II a number of people contributed to a mathematical theory of signals and noise, notably Norbert Wiener and Steven O. Rice. In 1950 James Lawson and George Uhlenbeck published the influential *Threshold Signals*, which discussed the relationship between the receiver filter and the output signal-to-noise ratio and gave a procedure for approximating the optimum filter.[58]

Analysis of seismic data, like analysis of radar data, stimulated the development both of computing technology and signal-processing techniques. Texas Instruments, originally a manufacturer of seismic instruments used in petroleum exploration,[59] began in 1956 to design a digital computer for processing seismic data.[60] Signal-processing technique was advanced by, among others, Enders Robinson. In the early 1950s he showed how to derive the desired reflection signals from seismic data, carrying out one-dimensional deconvolution.[61] The digitization and calculations were carried out by hand on a

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[57]Bernard Widrow personal communication 2 February 1998. Widrow wrote the following also: "During the summer of 1959, Widrow worked at Lincoln Lab. He contacted Bob Price about the radar data. He told them about his theory of quantization noise. He suggested that they could have used 2 bits per sample instead of 8, and gotten the same correlation result. They re-quantized to 2-bits per sample and re-ran the correlation and found the moon in the same place. They re-ran the correlation with 1-bit samples, and still got the moon in the same place."

[58]Burdic *op. cit.*, p. 12. *Threshold Signals* was Volume 24 of the celebrated series of books that summarized and systematized the work done during the war at MIT's Radiation Laboratory. It was based on the work of many investigators during the war.

[59]Geophysical Service Incorporated (GSI) was founded in 1930 to offer reflection seismograph exploration services to the oil industry, and by 1939 it had crews working in nine countries around the world. During the war, GSI assembled radar equipment and manufactured airborne magnetometers for the government. Texas Instruments was formed in 1950 from the manufacturing operations of GSI. [*The Leading Edge*, October 1996, p. 1151.]

[60]Harvey G. Cragon, "The early days of the TMS320 family" (*Texas Instruments Technical Journal*, vol. 13 (1996), no. 2, pp. 17–26).

[61]Jerry M. Mendel, "Seismic modeling problems in reflection seismology" (*IEEE ASSP Magazine*, vol. 3 (1986), no. 2, pp. 4–17). Robinson's Ph.D. thesis *Predictive Decomposition of Time Series with Applications to Seismic Exploration* (completed at MIT in 1954) was reprinted in full in *Geophysics* (vol. 32 (1967), pp. 418–484).

desk calculator; the deconvolution of 32 traces, each one 600 to 800 readings, took the entire summer of 1951.[62] In the spring of 1952 Robinson and Howard Briscoe programmed the MIT Whirlwind digital computer to do the numerical filtering at high speed.[63] A group at the Raytheon company contracted with MIT to do programming and computation tasks relating to the analysis of seismograms, and in March 1954 Raytheon offered to the industry at large what must have been the first commercial digital-signal-processing service.[64]

In the 1950s the economy was growing, and many companies increased their R&D budgets. Higher education was growing even faster, and, added to this, government funding of research increased markedly, particularly after the launch of Sputnik in 1957. Hence there was much more research in science and engineering, and growth of the professional societies was one consequence. While membership in the AIEE increased modestly during the decade, reaching 65,000, IRE membership almost tripled, reaching 90,000.[65]

The IRE Professional Group on Audio concerned itself with microphones, loudspeakers, disk recording and reproduction, stereo sound reproduction, film recording and reproduction, magnetic recording, electroacoustic measurement, and speech communication systems (telephone, radio broadcasting, public-address systems, and bandwidth-conserving systems).[66] Some

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[62]Robert Dean Clark, "Enders Robinson" (*Geophysics: The Leading Edge of Exploration*, February 1985, pp. 16–20).

[63]Gaining access to the Whirlwind computer was not easy for the MIT Geophysical Analysis Group. In response to Robinson's request for five hours per week, a meeting was called at the MIT President's office which included Julius Stratton (MIT Vice President), Jay Forrester (director of the Whirlwind project), head of the Geology and Geophysics Department, Robinson, and others. The outcome was that the MIT Geophysical Analysis Group was granted one hour per week. [Robinson personal communication 8 January 1998.]

[64]Robinson personal communication 8 January 1998, and Richard F. Clippinger, Bernard Dimsdale, and Joseph H. Levin, "Utilization of electronic digital computers in analysis of seismograms" (Waltham, MA: Raytheon Manufacturing Company, 29 March 1954). See also three reports from the MIT Geophysical Analysis Group (GAG): Enders A. Robinson, "Linear operator study of a seismic profile of the Texas Company" (MIT GAG Report No. 4, Cambridge, MA; 1953; 181 pp.); Enders A. Robinson, Stephen M. Simpson, and Mark K. Smith, "On the theory and practice of linear operators in seismic analysis" (MIT GAG Report No. 5, Cambridge, MA; 1953; 95 pp.); and Enders A. Robinson, Stephen M. Simpson, and Mark K. Smith, "Further research on linear operators in seismic analysis" (MIT GAG Report No. 6, Cambridge, MA; 1954; 203 pp.).

[65]John Ryder and Donald G. Fink, *Engineers & Electrons: A Century of Electrical Progress* (New York: IEEE Press, 1984), p. 216.

[66]This listing of technical areas comes from the subjects of the eight papers contained in the 50th anniversary issue of *Proceedings of the IRE* (May 1962) in "Section 3: Audio", which was prepared with the assistance of the Professional Group on Audio.

of the areas of research mentioned in this chapter were concerns of other IRE Groups; filter design, for example, was an important subject for the IRE Professional Group on Circuit Theory (which evolved into the IEEE Circuits and Systems Society). The AIEE, as well, represented engineers doing some of the work mentioned, and leaders of electrical engineering often published in both AIEE and IRE journals. For example, Claude Shannon's "A symbolic analysis of relay and switching circuits" (which a historian of computing has praised as "a landmark in that it helped to change digital circuit design from an art to a science")[67] appeared in the AIEE *Transactions*, while his argument for PCM mentioned in Chapter 1 appeared in the IRE *Proceedings*.[68]

At the end of the 1950s there occurred a technological advance that was to have an enormous impact on all of electronics and especially on the field of signal processing. Indeed, it may be argued that it was crucial to the emergence of a recognized field of signal processing. In February 1959 Jack Kilby of Texas Instruments filed a patent for the integrated circuit—a set of electronic components and their interconnections on a single slice of silicon or other semiconductor. Some six months later Robert Noyce and Jean Hoerni at Fairchild Semiconductor demonstrated the so-called planar process by which the components could be economically connected.[69] Up to this time the transistor was not revolutionary: as a discrete component it was comparable in cost and performance with electron tubes.[70] It was through the integrated circuit that the transistor revolutionized technology.

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[67]Herman Goldstine quoted in Neil J.A. Sloane and Aaron D. Wyner, eds., *Claude Elwood Shannon: Collected Papers* (New York: IEEE Press, 1993), p. xii.

[68]Claude Shannon, "A symbolic analysis of relay and switching circuits" (*Transactions of the AIEE*, vol. 57 (1938), pp. 713–723), and Bernard M. Oliver, John R. Pierce, and Claude Shannon, "The philosophy of PCM" (*Proceedings of the Institute of Radio Engineers*, vol. 36 (1948), pp. 1324–1332).

[69]Ernest Braun and Stuart Macdonald, *Revolution in Miniature: The History and Impact of Semiconductor Electronics*, second edition (Cambridge: Cambridge University Press, 1982), p. 88.

[70]Even in the 1950s the transistor had important advantages—smaller size, greater robustness, lower power—that made it much better than the electron tube for certain applications, such as hearing aids and missile-guidance systems.