Chapter 2

Birth Certificate of the Information Age: The Annus Mirabilis 1948

What Was Happening In 1948

movies people were watching:
Hamlet with Laurence Olivier
Walter Huston's *Treasure of the Sierra Madre*

TV shows people were watching:
"Hopalong Cassidy"—the first of the TV Westerns, it began in 1948
"The Howdy Doody Show"
"Meet the Press"

music people were listening to:
songs of Bing Crosby and Frank Sinatra

books people were reading:
Alfred Kinsey's *Sexual Behavior of the Human Male*
Norman Mailer's *The Naked and the Dead*
B.F. Skinner's *Walden Two*

In the history of science the year 1666 is known as Isaac Newton's *annus mirabilis* (amazing year). In that year that he wrote two papers on mechanics, "On violent Motion" and "The lawes of Motion", and a treatise on the new mathematics he had invented, which he called the method of fluxions and which we know today as calculus.[1] Albert Einstein's *annus mirabilis* was 1905, when he published three classic papers that presented, respectively, the hypothesis of the quantum nature of light, the statistical physics of Brownian motion, and the special theory of relativity.[2]

The year 1948 may be regarded as the *annus mirabilis* in the emergence of the discipline of signal processing. For in that year Claude Shannon published the epoch-making "A mathematical theory of communication"; Bernard Oliver, John Pierce, and Claude Shannon published the classic argument for the use of pulse-code modulation; modern digital methods of spectrum estimation were introduced; error-correcting codes were introduced; audio engineering achieved a new prominence; and the IEEE Signal Processing Society, albeit under a different name, was established. In addi-

---

[1]Richard Westfall, in his biography of Newton [*Never at Rest* (Cambridge: Cambridge University Press, 1980)], argues that one should talk instead of three *anni mirabiles* (1664, 1665, and 1666) and that myth has exaggerated how much Newton accomplished in this period (although "By any other standard than Newtonian myth, the accomplishment of the *anni mirabiles* was astonishing") [pp. 140–175, quotation on p. 174].

[2]Abraham Pais, '*Subtle is the Lord . . .*'—*The Science and Life of Albert Einstein* (Oxford: Oxford University Press, 1982), p. 522.

tion, that year saw a demonstration of the first stored-program computer and the announcement of the invention of the transistor, heralding two new technologies that would later greatly stimulate signal processing. Before discussing these and other achievements in more detail, let us set the scene.

When the year 1948 began, World War II was only two and a half years in the past. There was political turmoil around the globe: conflict between the newly created states of India and Pakistan over how the subcontinent should be partitioned (and in January Mahatma Gandhi was assassinated by a Hindu who resented Gandhi's role in the partitioning); civil war in China between the Nationalists headed by Chiang Kai-shek and the Communists headed by Mao Tse-tung; creation of two states, divided by the 38th parallel, in Korea; conflict between Jews and Arabs following the British evacuation of Palestine and proclamation of the state of Israel; and polarization of European states into a Communist bloc and a Western bloc (with tensions heightened in April when the Soviets denied the Western Allies land access to West Berlin, leading to the supply of that city by air for 18 months). But there were reasons to be optimistic about the future. In the United States the economy was strong, and the approval by Congress in April of what became known as the Marshall Plan promised to speed European economic recovery. People everywhere hoped that the wartime technological advances would now be turned to raising the standard of living.

There were jet aircraft and the promise of atomic energy, but for many people the most impressive of the new technologies was electronics, which came out of World War II a much larger field than it entered. Prior to the war, radio was by far the largest area of electronics, though electron tubes were used also for long-distance telephony and carrier telephony (using one line for many conversations simultaneously), for sound movies, in phonographs and public-address systems, and in many instruments. During the war there arose new applications of electronics—such as radar, sonar, and computing—and earlier areas of application—such as communications, electronic navigation, instrumentation, and control systems—expanded enormously. And, just after the war, industrial electronics emerged as a major field, and television and FM radio seemed poised for commercial success.

The burgeoning of electronics affected the two large professional societies in the United States that represented those we would now call electrical engineers: the American Institute of Electrical Engineers (AIEE) and the Institute of Radio Engineers (IRE). The larger of the two, the AIEE, had been founded in 1884, and most of its members worked in electric power, industry applications, wired communications, or instrumentation.

The IRE, founded in 1912, differed from the AIEE not only in technical area but also in that, from its inception, it aimed to be a transnational organization (hence there was never an "American Institute of Radio Engineers").[3]

The growth of electronics meant that it came increasingly to be part of traditional fields of electrical engineering and thus within the scope of the AIEE. Indeed, by 1963, when the AIEE and the IRE merged to form the Institute of Electrical and Electronics Engineers, about half of the members of the AIEE were concerned with electronics.[4]

For the IRE the growth of electronics meant not only increased size but also a much wider technical field. Because it was often radio engineers who pioneered new areas of electronics, it was natural that the IRE represent the new areas. Yet the increased diversity within the Institute as a whole suggested to its leaders that there be established groups of members in particular specialties, and in 1948 the IRE Professional Group System was established. Though there had earlier been IRE technical committees for different specialties, this was new in that each Group was a membership organization (open to IRE members) that could publish its own transactions and organize its own conferences. The IRE Group System, adopted by the IEEE at the time of the merger in 1963, evolved into the present system of IEEE Technical Societies.[5]

The first of these technical groups to be set up was the Professional Group on Audio, whose petition for formation was approved by the IRE Executive Committee on 2 June 1948.[6] Oliver Angevine, Leo Beranek, and Benjamin Bauer were among those who worked to establish the new organization. The Group organized sessions at IRE conferences and soon began publishing its own transactions, as well as a newsletter.

The Group's interests included phonograph and magnetic recording, amplifiers, loudspeakers, audio measurement techniques, electroacoustics, and speech communications. These involved what may be called analog signal processing and drew upon technologies developed during World War II. For example, researchers at the Electro-Acoustic Laboratory and the Psycho-Acoustic Laboratory at Harvard University greatly advanced the analy-

---

[3]John Ryder and Donald G. Fink, *Engineers & Electrons: A Century of Electrical Progress* (New York: IEEE Press, 1984), pp. 209–215.

[4]Ivan S. Coggeshall, "IEEE's endowment in electronics from AIEE" (*Electrical Engineering*, vol. 82 (1963), pp. 2–20).

[5]Ryder and Fink *op. cit.*, pp. 216–217.

[6]Institute of Radio Engineers, Executive Committee, *Minutes* 2 June 1948.

sis and processing of signals in the audio range. Analog filters for determining the spectra of speech, music, or noise were designed. The performance of amplifiers and of communication and recording equipment was improved, as in the "clipping" and reshaping of speech signals to increase the signal-to-noise ratios in communications in high-noise environments, such as military aircraft. Other signal-processing techniques came out of extensive wartime work on underwater sound, such as filters and spectral-shaping circuits to emphasize the noises of submarines.[7]

So although signal processing did not exist as a discipline in 1948, the IRE Professional Group on Audio concerned itself with work that, over the next two decades, contributed to the emergence of the new field. There were, however, other lines of work that contributed, and in looking back at 1948 we should consider these other lines of work and may regard them as part of the heritage of signal processing.

The year 1948 stands out in a history of technology because it saw the publication of Claude Shannon's "A mathematical theory of communication".[8] Robert Lucky has written, "I know of no greater work of genius in the annals of technological thought."[9] Irving Reed has commented, "By this landmark paper and his several subsequent papers on information theory he has altered most profoundly all aspects of communication theory and practice."[10]

Shannon, a researcher at Bell Telephone Laboratories, analyzed communication as the transmission of a message from a source through a channel to a receiver. (See Figure 1.) He quantified this process, measuring the information source in bits per second, and found limits to the channel capacity. Perhaps the most celebrated result contained in the original paper is the proof that the capacity of a band-limited channel, in bits per second,

Should these papers be posted?

---

[7]Leo Beranek personal communication 2 January 1998.

[8]Claude Shannon, "A mathematical theory of communication" (*Bell System Technical Journal*, vol. 27 (1948), pp. 379–423, 623–656). Several months later Shannon published another paper, which elaborated and extended the first paper and which adopted an engineering rather than a strictly mathematical viewpoint: "Communication in the presence of noise" (*Proceedings of the IRE*, vol. 37 (1949), pp. 10–21). This paper is reprinted in *Proceedings of the IEEE*, vol. 86 (1998) along with an introductory paper written by Aaron D. Wyner and Shlomo Shamai (Shitz): "Introduction to 'Communication in the presence of noise' by C.E. Shannon" (*Proceedings of the IEEE*, vol. 86 (1998), pp. 442–446). (B) (B)

[9]Robert W. Lucky, *Silicon Dreams: Information, Man, and Machine* (New York: St. Martin's Press, 1989), p. 37.

[10]Quoted in Neil J.A. Sloane and Aaron D. Wyner, eds., *Claude Elwood Shannon: Collected Papers* (New York: IEEE Press, 1993), p. xiii.

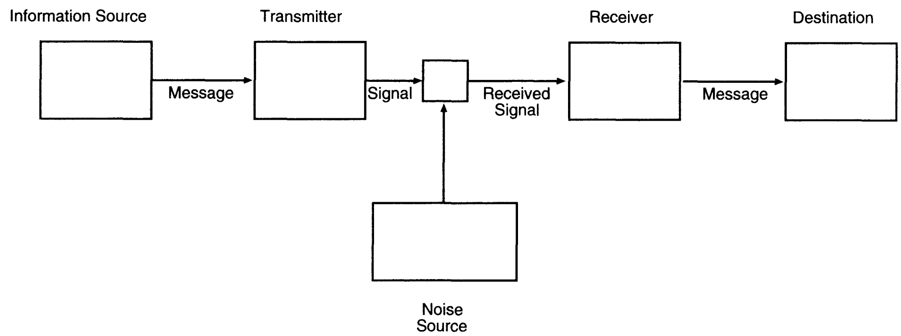


FIGURE 1. This is Figure 1 from "A mathematical theory of communication", showing Shannon's conception of a general communication system. (Redrawn after Figure 1 from Claude Shannon, "A mathematical theory of communication"(*Bell System Technical Journal*, vol. 27 (1948), pp. 379–423, 623–656).)

equals the bandwidth times the logarithm (base 2) of the signal-to-noise ratio plus 1.[11] Shannon, of course, was not alone in creating a discipline of information theory: he was much influenced by a 1928 paper by Ralph V.L. Hartley, beginning where Hartley left off, and by Norbert Wiener, who emphasized the statistical nature of communication.[12] A number of other pioneers of the new discipline, including Dennis Gabor and Philip M. Woodward, made vital contributions.[13]

Another landmark publication of 1948 was "The philosophy of PCM", written by Bernard M. Oliver, John R. Pierce, and Claude Shannon.[14] Pulse-code modulation (PCM) is a means of transmitting information in the form of on-or-off pulses. In telephony and radio, signals were traditionally transmitted through amplitude modulation (AM), though by 1948 frequency modulation (FM) had come into widespread use as well. With traditional AM or FM, the signal is analog (varying continuously), while with PCM the signal is digital (represented in discrete units). PCM had been invented by Paul M. Rainey in 1926 and independently by Alec H. Reeves in 1937, but

[11]Sidney Millman, ed., *A History of Engineering and Science in the Bell System: Communication Sciences (1925–1980)* (AT&T Bell Telephone Laboratories, 1984), p. xiv.

[12]Wiener's *Extrapolation, Interpolation, and Smoothing of Stationary Time Series* (1949), referred to below, was originally issued as a classified report in 1942.

[13]Lucky *op. cit.*, p. 38, and William S. Burdic, *Underwater Acoustic Signal Analysis* (Englewood Cliffs, NJ: Prentice-Hall, 1984), p. 12.

[14]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).

little noticed.[15] Oliver, Pierce, and Shannon were so struck by its advantages, explained more fully in Chapter 4, that they "expected PCM to sweep the field of communications". This did not happen, even though their article was extremely influential. Over several decades, receiving boosts from the development of integrated-circuit technologies, the proliferation of computers, and the use of optical fiber for communications, PCM did indeed become widespread.[16]

A dominant trend in many areas of technology in the second half of the 20th century has been the replacement of analog methods by digital methods. Besides the Oliver-Pierce-Shannon article, there were other signs of this trend in 1948. Because of the way most radar and sonar systems worked, both radiating and receiving pulses of electromagnetic radiation, many engineers during World War II dealt with discrete data. The work on fire control and other radar systems therefore generated a large literature on sampled-data control systems.[17] One issue faced by radar engineers—and later by engineers in many other fields—was estimating a continuous spectrum, such as the power spectrum of a radar signal, on the basis of sampled data. In 1948 Maurice Bartlett in England, and the following year John Tukey in the United States, began developing the digital methods of spectrum estimation that have remained in use ever since.[18]

One advantage of digital signals was made clear in 1948 by Richard W. Hamming's invention of error-correcting codes. Hamming proposed encoding a message in blocks of binary digits, with each block satisfying certain algebraic equations, so that if an error occurred in transmission (a 0 converted into a 1 or vice versa) the recipient could not only detect this,

---

[15]Millman *op. cit.*, pp. 403–404.

[16]John R. Pierce and A. Michael Noll, *Signals: The Science of Telecommunications* (New York: Scientific American Library, 1990), pp. 78–79; the quotation is from p. 79.

[17]Kaiser reports [James F. Kaiser, "Digital filters" (Chapter 7 of *System Analysis by Digital Computer*, Franklin F. Kuo and James F. Kaiser, eds. (New York: John Wiley, 1966), pp. 218–285)] that this work yielded a well-developed theory of *z*-transforms. Ben Gold [*The Institute*, June 1997, p. 13] has said that "the major 'spark' that generated my interest [in digital signal processing] was a chapter in 'Theory of Servomechanisms' (a volume in the Radiation Laboratory Series) on sampled-data systems."

[18]Millman *op. cit.*, p. 75. Two standard methods of measuring the average power spectral density are the frequency smoothing method (FSM) and the time averaging method (TAM). FSM was introduced by Einstein in 1914, rediscovered by Norbert Wiener in 1930, and rediscovered by Percy John Daniell in 1946. TAM was proposed by Bartlett in 1948 and rediscovered by P.D. Welch in 1967. [William A. Gardner, "History and equivalence of two methods of spectral analysis" (*IEEE Signal Processing Magazine*, vol. 13 (1996), no. 4, pp. 20–23).]

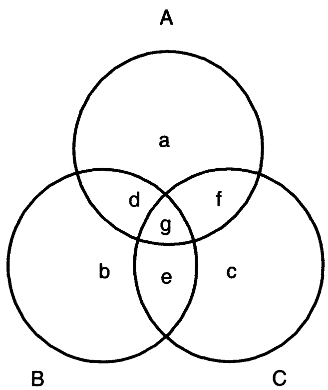
> To get to [Bell Labs in] NYC I would go a bit early to the Murray Hill, NJ location where I worked and get a ride on the company mail delivery car. Well, riding through north Jersey in the early morning is not a great sight, so I was ... reviewing the rectangular codes. Suddenly, and I can give no reason for it, I realized if I took a triangle and put the parity checks along the diagonal ... then I would have a more favorable redundancy.... A few miles of thought on the matter [and] I realized a cube of information bits [would be better] .... It was soon obvious (say five miles) a $2 \times 2 \times 2 \times \ldots \times 2$ cube, with n+1 parity checks would be the best ....
>
> — Richard W. Hamming[1]
>
> [1]Richard W. Hamming, *The Art of Doing Science and Engineering: Learning to Learn* (Amsterdam: Gordon and Breach, 1997), pp. 139–140. Harold S. Black first conceived the negative feedback amplifier [Harold S. Black, "Inventing the negative feedback amplifier" (Spectrum, vol. 14, no. 12 (December 1977), pp. 54–60)] while taking the ferry from New Jersey to New York City, and Bishnu Atal's ideas for linear predictive coding (LPC) came first while he was traveling by train from Bell Labs in Murray Hill, New Jersey to the Polytechnic Institute of Brooklyn [Atal personal communication 2 February 1998]. On the basis of these three examples, one might theorize that travel from New Jersey to New York stimulates great thoughts. More prosaically, one might point out that the three inventors were Bell Labs researchers and that Bell Labs facilities were located on both sides of the New Jersey–New York boundary.

but also correct the error. (See Figure 2). Hamming showed how to achieve this efficiently and, working with Bernard D. Holbrook, even how to design equipment to do the checking and correcting automatically, which, in the pre-computer era, was not an easy task.[19]

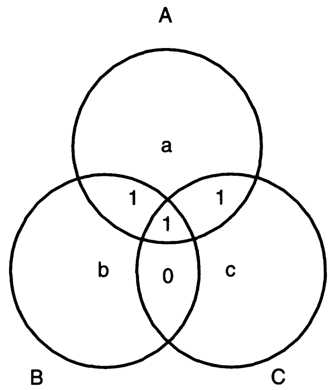
In June 1948 Bell Telephone Laboratories announced the invention of the transistor, a solid-state amplifying device. (See Figure 3.) Even as a discrete component, its small size and low power requirements would in the 1950s and 1960s expand the realm of signal processing, and this effect was magnified manyfold when it later became possible to incorporate huge numbers of transistors on a single chip of silicon. Later chapters, especially Chapter 7, will make these effects clear.

In 1948 there was a milestone in computer history also: on 21 June 1948 a small prototype computer, built at Manchester University, became the first operational stored-program electronic computer.[21] Full-size stored-

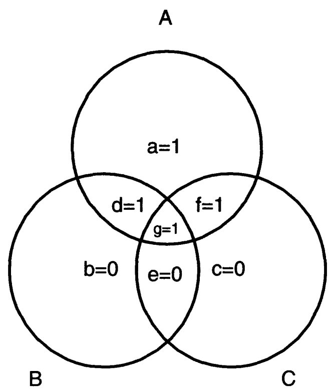
[19]Millman *op. cit.*, p. 53.



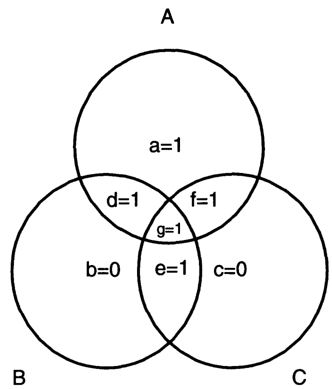
Three overlapping circles with the regions a through g defined



Insertion of the digits of the signal



Determination of transmitted signal



Received signal including error in e

FIGURE 2. These figures illustrate Hamming's error-correcting code. For each block of four binary digits d, e, f, g, send seven digits a, b, c, d, e, f, g, where a, b, and c are chosen so that the number of 1s in each of the three overlapping circles A, B, C is even. Then if an error occurs in any one of the digits a through g, it can be detected and corrected. Suppose, for example, that the original message is 1 0 1 1. Then, a would be 1 and b and c would be 0, so you would send 1 0 0 1 0 1 1. Suppose the fifth digit is received incorrectly. The receiver can see this immediately, since the two lower circles have an odd number of 1s (hence the common element in those two circles must be the erroneous).[20] (Redrawn after figures on pp. 18 and 19 of John G. Truxal, *The Age of Electronic Messages* (Cambridge, MA: MIT Press, 1990).)

---

[20]John G. Truxal, *The Age of Electronic Messages* (Cambridge, MA: MIT Press, 1990), pp. 16–19.

FIGURE 3. William Shockley (left), Walter Brattain (standing), and John Bardeen received the Nobel Prize in 1956 for their invention of the transistor. (Bell Labs photo reproduced by permission.)

program computers were under construction in many places—the EDSAC by Maurice Wilkes at Cambridge University, the BINAC by Presper Eckert and John Mauchly at the University of Pennsylvania, John von Neumann's computer at the Institute for Advanced Study in Princeton, and others—but, as with the transistor, several years would pass before computers attained commercial success. Computers, too, would over the next decades have enormous influence on the development of signal processing.

---

[21]Martin Campbell-Kelly and William Aspray, *Computer: A History of the Information Machine* (New York: Basic Books, 1996), p. 100. The ENIAC, the first large general-purpose electronic digital computer, was completed in 1946, but it was programmed with switches and patch-cords. Later it was modified to operate as a stored-program computer. [Michael R. Williams, *A History of Computing Technology* (Englewood Cliffs, NJ: Prentice-Hall, 1985), pp. 275–287.]

Enders Robinson: I came back to MIT in the fall of 1950, and I was in the Mathematics Department as a graduate research assistant. I was working under Norbert Wiener to find applications for his time-series analysis. As you know, Norbert Wiener was an eminent mathematician at MIT, and he worked in generalized harmonic analysis back in 1930. He always felt that people didn't realize that was probably his most important contribution. But during World War II, he worked on prediction theories for anti-aircraft fire control. He developed a theory—classified at the time—but published by MIT Press in 1949. We used the book when I was an undergraduate student there, so I was familiar with it. By 1950, we were ready to apply it. Meanwhile, Wiener had written another book called *Cybernetics* which was first published about 1948. That book was an instant success; he was the one that introduced the word cybernetics.

So Wiener was a celebrity by 1950, and my research assistantship depended on finding applications of his work. Another MIT mathematics professor, George Wadsworth, my graduate advisor, was working in weather prediction which he originally started during World War II; Wiener's classified book had come out, but it was too difficult mathematically to be applied as such. So Wadsworth asked Norman Levinson, who was another eminent mathematician at MIT, to take Wiener's book and to simplify it into numerical algorithms that he, Wadsworth, could use. Levinson published these papers in the *Journal of Mathematics and Physics* in 1947. They were added as appendices to Wiener's 1949 book, so Levinson's algorithms with Wiener's theory became the way to do this type of thing. We could then apply it to geophysics because seismic records are essentially noisy records.[1]

[1]Enders Robinson oral-history interview 6 March 1997, pp. 2–3.

The potential impact of computers on society was made known to a wide audience by a book published in 1948, Norbert Wiener's *Cybernetics*, which compared biological systems with electrical communications- and control-systems.[22] It contained some discussion of signal processing, but a book Wiener published the following year, *Extrapolation, Interpolation and Smoothing of Stationary Time Series*, proved of much greater value for signal processing, while, not surprisingly, receiving much less popular notice.[23]

We have not yet mentioned one of the biggest stories of the year: in September Peter Goldmark, head of CBS Laboratories, presented a paper to

[22]Norbert Wiener, *Cybernetics, or Control and Communication in the Animal and the Machine* (Cambridge, MA: MIT Press, 1948).

[23]Norbert Wiener, *Extrapolation, Interpolation, and Smoothing of Stationary Time Series With Engineering Applications* (Cambridge, MA: MIT Press, 1949).

the Institute of Radio Engineers on "The Columbia Long-Playing Microgroove Recording System".[24] Actually, it was not this talk but a press conference and commercial release of the new long-playing (LP) record three months earlier that was the big story.[25] (See Figure 4.)

Long-playing records had been developed in the 1920s by Western Electric in order to provide sound for movies, and in the 1930s studios of the radio and music industries used 33⅓-rpm transcription machines. Goldmark and Columbia made important technological innovations, including a new cutting technique and a new lightweight pick-up arm, and faced the formidable business challenge of persuading record companies and customers to accept the new format.[26] The much longer playing time and the noticeably better sound helped them succeed.[27]

RCA responded to the Columbia long-playing record by introducing the 45-rpm microgroove record in 1949. Though 45s held just four minutes of music on a side, they were much smaller (so could fit on a bookshelf), could be changed rapidly, and could be sold at a much lower price. A record format that had been standard for twenty years thus faced two challengers in "the Battle of the Speeds".[28] The manufacture of 78s declined, but both the new speeds succeeded, the LP becoming most popular and the 45 maintaining huge sales, particularly to the "youth market", for decades.[29] The

---

[24]Peter Goldmark, "The Columbia Long-Playing Microgroove Recording System" (*Proceedings of the IRE*, vol. 37 (1949), pp. 923–927).

[25]William E. Butterworth, *Hi-Fi: From Edison's Phonograph to Quadraphonic Sound* (New York: Four Winds Press, 1977), pp. 156–166.

[26]In developing its lightweight pick-up arm, Columbia drew on Frederick Hunt's work on a lightweight arm in the late 1930s. An account of Hunt's work is contained in the Beranek oral-history interview [part beginning with Cruft Laboratory].

[27]Steven Lubar, *Infoculture: The Smithsonian Book of Information Age Inventions* (Boston: Houghton Mifflin, 1993), p. 184, and Millard, p. 205.

[28]When Emile Berliner introduced the Gramophone in the 1890s, the records turned at 70 revolutions per minute. In the 1920s the use of synchronous motors to drive turntables caused a change to 78 rpm: the motor, powered by 60-Hertz alternating current, turned at 3600 rpm, was attached to a 46:1 gear reduction (giving 78.26 rpm). [Butterworth *op. cit.*, p. 30.]

[29]Andre Millard, *America on Record: A History of Recorded Sound* (Cambridge, UK: Cambridge University Press, 1995), pp. 206–208. As late as 1954, however, 78s still outsold the other formats: in that year the U.S. record industry shipped 121 million 78s worth $24 million, 76 million 45s worth $21 million, and 24 million LPs worth $22 million [Editors of Electronics, *An Age of Innovation: The World of Electronics 1930–2000* (New York: McGraw-Hill, 1981), p. 98].

FIGURE 4. In this photograph Peter Goldmark grimly demonstrates data compression: the small stack of LPs in the center contains the same music as the two large stacks of 78–rpm records. (CBS photo reproduced by permission.)

new record formats stimulated interest in music and reawakened the desire to have as full an experience of music at home as in live performance.

The late 1940s witnessed another new recording medium. Invented in 1898 by the Danish engineer Valdemar Poulsen, magnetic recording did not achieve much commercial success until the German company AEG (Allgemeine Elektricitäts-Gesellschaft) replaced the steel wire or steel tape that had been used as the recording medium with coated plastic tape in its

Magnetophone, first marketed in 1935.[30] This type of magnetic recording came to the United States after the war, and in 1948 the major recording studios in the United States adopted magnetic recording. A vital advantage was that it permitted easy editing.[31] Similarly, and at about the same time, the film industry began using magnetic sound-recording for the original takes and for editing,[32] and, as part of the "hi-fi movement", tape recorders began to be sold in significant numbers to individuals.[33]

In 1934 radio and phonograph salesmen had begun using the term 'high fidelity'.[34] Though not defined precisely, it meant greater faithfulness in the sound coming from the radio or phonograph to the original sound.[35] In the 1930s, however, it was little more than an advertising slogan, as radio and phonograph engineers worked mainly to lower the price of equipment rather than to improve its performance.[36] There was also the belief among manufacturers that most people preferred the mellow sound and low fidelity of existing sets to the sharp sound of higher fidelity.[37]

Many music enthusiasts, however, did not accept the quality of sound available from the radios and phonographs they could purchase and began experimenting with putting together their own sound systems. Some of

---

[30]AEG engineers made other vital improvements, notably a shifting of the audio signal to a much higher frequency, where the magnetic material displays a more nearly linear response. This technique, called electrical bias, had been patented in the United States in the 1920s, but it was not then put into practice, nor was it known to the German engineers. [Millard *op. cit.*, pp. 195–197.]

[31]Oliver Read and Walter L. Welch, *From Tin Foil to Stereo: Evolution of the Phonograph* (Indianapolis, IN: Howard W. Sams, 1959), p. 350.

[32]Max C. Batsel and Glenn L. Dimmick, "Film recording and reproduction" (*Proceedings of the IRE*, vol. 50 (1962), pp. 745–751).

[33]Ampex, which came to dominate the U.S. market in the 1950s, began selling tape recorders in 1948 [*U.S. Consumer Electronics Industry Today* (Arlington, VA: Consumer Electronics Manufacturers Association, 1997), p. 83].

[34]Both the Oxford English Dictionary and the Merriam-Webster Collegiate Dictionary give 1934 as the date for the earliest use of 'high fidelity'.

[35]Radio engineers had given clear quantitative meanings to terms such as 'sensitivity', 'selectivity', and 'fidelity', but not to 'high fidelity'. See 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).

[36]Frederik Nebeker, "Harold Alden Wheeler: a lifetime of applied electronics" (*Proceedings of the IEEE*, vol. 80 (1992), pp. 1223–1236).

[37]Roland Gelatt, *The Fabulous Phonograph: From Tin Foil to High Fidelity* (Philadelphia: J.P. Lippincott, 1954), p. 297.

them were amateur radio operators, and some of them had worked with communications, radar, or other electronics for the military in the war. They found that by judiciously combining amplifiers, pickups, turntables, receivers, speakers, and other components purchased from radio supply houses, whose supplies were augmented by surplus military equipment, they could achieve a much better sound. It was in 1947 and 1948 that this hi-fi movement began.[38] What had been a hobby of a relatively small number of people at the end of World War II soon produced a multimillion-dollar component manufacturing business, with annual sales in the U.S. reaching $140 million in 1954.[39] In the next chapter we see how audio engineering both responded to and stimulated the hi-fi movement.

[38]Gelatt *op. cit.*, pp. 297–298, and Read and Welch *op. cit.*, pp. 343–352.

[39]Gelatt *op. cit.*, p. 298, Millard *op. cit.*, pp. 208–211, and Read and Welch *op. cit.*, pp. 343–352.