Opening Black's Box

Rethinking Feedback's Myth of Origin

DAVID A. MINDELL

> *The specific triumph of the technical imagination rested on the ability to dissociate lifting power from the arm and create a crane: to dissociate work from the action of men and animals and create the water-mill: to dissociate light from the combustion of wood and oil and create the electric lamp.*
>
> —Lewis Mumford

> *The engineer who embarks on the design of a feedback amplifier must be a creature of mixed emotions.*
>
> —Hendrik Bode

Like any modern episteme worthy of the name, the theory of feedback has a myth of origin. On a sunny August morning in 1927, Harold Black, a twenty-nine-year-old systems engineer, rode the Lackawanna ferry to work at the Bell Telephone Laboratories. Many Bell engineers lived in New Jersey, and on the early morning ferry rides across the Hudson to the Manhattan laboratories they frequently gathered on the forward deck. This morning Black stood alone, staring at the Statue of Liberty, and had an epiphany: "I suddenly realized that if I fed the amplifier output back to the input, in reverse phase, and kept the device from oscillating (singing, as we called it then), I would have exactly what I wanted: a means of canceling out the distortion in the output."[1] As it happened, the *New York Times* that day con-

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[1] Harold S. Black, "Inventing the Negative Feedback Amplifier," *IEEE Spectrum* 14

tained a blank page, and Black sketched his idea, "a simple canonical diagram of a negative feedback amplifier plus the equations for the amplification with feedback." He rushed into work, asked a technician to wire up a prototype, and gave birth to a foundational circuit of modern electronics. This story has become enshrined as one of the central "flashes of insight" in electrical engineering in this century, periodically retold as an inspiration for engineers.[2] A common textbook on control engineering reprints the story of Black's vision verbatim in the first chapter.[3]

At Bell Laboratories from 1927 to 1940, the legend goes, Black, Harry Nyquist, and Hendrik Bode laid the foundations of feedback control that engineers then applied to all types of closed-loop systems, from servomechanisms to thermostats, fire control systems to automatic computers.[4] More than other contemporary narratives of control systems such as automatic pilots or servomechanisms, this story of feedback earned a place in engineering legend and college textbooks. It produced design methods and graphical techniques that carry their author's names (the Bode plot, the Nyquist diagram) and earned telephone engineering a claim to priority in feedback history. Feedback theory, moreover, formed the basis of cybernetics, systems theory, and a host of other post–World War II information sciences, so Black's invention is hailed as a foundation of the information age.

Feedback is indeed a fundamental concept in twentieth-century technology, and the Bell Labs feedback theorists did lay critical foundations for it. But the origin myth effaces its sources. It skips over the inventors themselves and the ways in which their backgrounds and prior experience influ-

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(December 1977): 54–60. George Stibitz's memoir describes the early morning ferry rides; "The Zeroth Generation," manuscript, 1993, Stibitz Papers, Dartmouth College, 54. For the quotations from Mumford and Bode, see Lewis Mumford, *Technics and Civilization* (New York, 1934), 33; Hendrik Bode, "Relations Between Attenuation and Phase in Feedback Amplifier Design," *Bell System Technical Journal* 19 (July 1940): 421–54.

[2] For other accounts of Black's invention, see Hendrik Bode, "Feedback: The History of an Idea," *Proceedings of the Symposium on Active Networks and Feedback Systems* (Brooklyn, 1960), reprinted in *Selected Papers on Mathematical Trends in Control Theory*, ed. Richard Bellman (New York, 1964); M. J. Kelley, "Career of the 1957 Lamme Medalist Harold S. Black," *Electrical Engineering* 77 (1958): 720–22; Prescott C. Mabon, *Mission Communications: The Story of Bell Laboratories* (Murray Hill, N.J., 1975), 39–40. Among historians' accounts the most thorough is Stuart Bennett, *A History of Control Engineering, 1930–1955* (London, 1993), chap. 3, "The Electronic Negative Feedback Amplifier." See also E. F. O'Neill, ed., *A History of Science and Engineering in the Bell System: Transmission Technology (1925–1975)* (Murray Hill, N.J., 1985), chap. 4, "Negative Feedback"; Ronald Kline, "Harold Black and the Negative-Feedback Amplifier," *IEEE Control Systems* (August 1993): 82–85; and a short film, *Communications Milestone: Negative Feedback* (Bell Telephone Laboratories, 1977).

[3] Richard C. Dorf, *Modern Control Systems*, 5th ed. (Reading, Mass., 1995).

[4] Hendrik W. Bode, *Synergy: Technical Integration and Technological Innovation in the Bell System* (Murray Hill, N.J., 1971), 138–40.

enced their work. It reveals little about the concrete problems these men worked on when they produced their solutions. The story also removes feedback theory from its engineering culture, that of the telephone network between the world wars. Black's version also does not account for the relationship of his feedback amplifiers to prior traditions of governors and self-regulating machinery.

Thus a reexamination of the sources is in order, retelling Black's legend not as a heroic tale but as the story of an engineer solving the technical problems of a particular place and time and trying to convince others to support his solutions. As it turns out, Black did not understand as much about feedback as he later recalled. To make his idea credible, he needed Nyquist's reformulation of the problem of stability and Bode's analysis outlining the tight constraints that a feedback amplifier had to meet. He also needed the Bell System. Negative-feedback amplifiers emerged from efforts to extend the telephone network across the continent, to increase the network's carrying capacity, and to make it work predictably in the face of changes in season, weather, and landscape—from the context, that is, of building a large technical system and operating it over a diverse and extended geography. Black, Nyquist, and Bode worked within a company that sought to translate ever more of the world into transmissible messages. This translation required, among other things, ever closer couplings of human and mechanical elements through the medium of sound, couplings that left a discernible mark on feedback theory. For telephone engineers, the network listened, and it spoke.

In 1934, the same year that Black published his amplifier, Lewis Mumford, in *Technics and Civilization*, noted technology's ability to abstract the world. "Men became powerful to the extent that they neglected the real world of wheat and wool, food and clothes," he wrote, "and centered their attention on the purely quantitative representation of it in tokens and symbols."[5] In light of Mumford's observation, a retelling of Black's story has greater significance than a simple corrective to the origin myth, for it concerns the historical emergence of electrical signals as representations of the world, the technologies developed to manipulate and transmit them, and the economic and organizational conditions that made those technologies possible. Black, Nyquist, and Bode contributed to an understanding of telephony as the transmission of abstract signals, separate from the electric waves that carried them. The AT&T engineers' increasing facility with creating, manipulating, and switching such signals prompted them to rethink the network not simply as a passive medium but as an active machine. Then the Bell System became not merely a set of voice channels but a generalized system, capable of carrying any signal as a new currency: information.

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[5] Mumford, 25.

Network Geography

The Bell System of 1900 was an engineer's dream: geographically expansive, reaching into all types of difficult terrain and climates, and yet always in control, tied to the central office. Still, in the first decade of the century American Telephone and Telegraph (AT&T) did not yet have its later hegemony. The company controlled only about half the telephones in the country, and long distance was the key to expanding that share. Originating in New York, the Bell System followed its own frontier on a western expansion.[6] From the turn of the century until the 1930s, AT&T expressed its technical milestones in geographical terms: the New York/Chicago line stood for carrier-frequency transmission; the New York/San Francisco transcontinental line stood for vacuum-tube repeaters; the Morristown trial simulated the entire country and represented the negative-feedback amplifier. "People assimilated telephony into their minds as if into their bodies," writes telephone historian John Brooks, "as if it were the result of a new step in human evolution that increased the range of their voices to the limits of the national map."[7]

THE PASSIVE NETWORK

Despite these ambitions, at the turn of the century the telephone network remained a passive device, as it had been since Bell's invention. Carbon microphones added energy from a battery to the weak acoustic signal from a speaker's voice, but once the wave entered the line it traveled to the receiver without further amplification, going the full distance on its original strength. In fact, impedance in the wire imposed considerable losses, known as "attenuation." Around 1900 the telephone network ran up against the limits of transmission, both in extension, which determined the furthest distance a signal could travel, and in economy, which determined the cost of sending a signal over shorter distances.

Weather exacerbated the problem. The standard method of transmission, even for long distances, was "open wire," which meant each circuit literally had its own wire, separated from others by a few inches of space. This separation minimized cross talk, where one conversation leaked to an adjacent wire, and also kept attenuation losses to a minimum. Telephone poles

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[6] For the general history of the Bell System, see John Brooks, *Telephone: The First One Hundred Years* (New York, 1975); Thomas Shaw, "The Conquest of Distance by Wire Telephony," *Bell System Technical Journal* 23 (October 1944); Leonard Reich, "Industrial Research and the Pursuit of Corporate Security: The Early Years of Bell Labs," *Business History Review* 54 (winter 1980): 511. See also Leonard Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876–1926* (New York, 1985), chaps. 7–8. For another interpretation of the semiotics of telephony, see Avital Ronell, *The Telephone Book: Technology, Schizophrenia, Electric Speech* (Lincoln, Neb., 1991).

[7] Brooks, 142.

with dozens of wires (familiar in turn-of-the-century urban scenes) distinguished this technology. In addition to cluttering the landscape, the lines were particularly vulnerable to snow and ice storms. Cables, an alternative to open wire, collected numerous small wires together into a thick bundle. They could be buried underground, which made them immune to weather and cheaper to install. But because the wires were of small diameter and packed tightly together, cables had higher losses than open wire, twenty to thirty times more signal attenuation, so they lowered the limits of transmission.

To push these limits, Michael Pupin of Columbia University and George Campbell of Western Electric, working simultaneously, developed the loading coil. By adding inductance at intervals along the wire, loading coils could decrease signal loss by a factor of three or four, and thus increase the maximum transmission distance proportionally.[8] Commercial installation began in 1904, and loading coils rapidly proliferated through the network, especially on cabled routes.[9] Still, the loading coil remained passive—it facilitated the propagation of the wave down the line but added no additional energy.

THE TRANSCONTINENTAL LINE: GEOGRAPHY AND STANDARDIZATION

Not only technical innovations but also organization and policy supported the network's expansion. John J. Carty, chief engineer of the Bell System in 1907, had a clear vision of the social role of the telephone network as "society's nervous system." He and his engineers vigorously pursued the goals of AT&T President Theodore Vail's famous motto: "One policy, one system, and universal service." Carty strongly supported science within the company. He had a vision of industrial research that translated corporate goals into technical problems to be solved in the laboratory (sometimes as much for protection against competition as for advancement).[10] One of Carty's longtime associates recalled him as a system-

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[8] James E. Brittain, "The Introduction of the Loading Coil: George A. Campbell and Michael I. Pupin," *Technology and Culture* 11 (1970): 36–57. See also the discussion of Brittain's article by Lloyd Espenschied, Joseph Gray Jackson, and John G. Brainerd, *Technology and Culture* 11 (1970): 596–603. Neal Wasserman, *From Invention to Innovation: Long-Distance Telephone Transmission at the Turn of the Century* (Baltimore, 1985).

[9] M. D. Fagan, ed., *A History of Engineering and Science in the Bell System: The Early Years (1875–1925)* (Murray Hill, N.J., 1975), 241–52.

[10] Ibid., 32–35, 44. Ironically, in a consolidation of research, Carty closed Western Electric's Boston engineering department, which had been investigating Lee De Forest's audion for use as an amplifier. Hugh Aitken argues that the closing of the lab may have cost the company several years toward making a practicable telephone amplifier. A proposed contract with Reginald Fessenden for radio technology also became a casualty of Vail's consolidation. "What slipped through the Telephone Company's fingers, in short, was a unique opportunity to come to grips with electronic technology," Aitken argues, countering other historians (Hoddeson and Reich) who view the move to a single department in New York as progress toward industrial research; see Hugh Aitken, *The*

builder in the Hughesian sense: "He recognized the interrelationship in the telephone business of operating methods, design of the plant, and the rate structure. . . . He had in mind that all of these factors must be considered in relations to one another."[11] And on all of these factors, Carty believed, science could be brought to bear.

And science he needed. By 1911, the state of the transmission art had hit its practical limit: "loaded" lines reached the 2,100 miles between New York and Denver, but the attenuation and distortion so mangled voice signals they were barely understandable. Yet in 1909 AT&T's technical management initiated a project to extend the Denver line to California, completing a transcontinental line. This geographical problem had a technical core. Bridging the distances required an amplifier or "repeater," an active device that added energy to the signal, unlike loading coils, which merely stemmed its decay.[12] To solve this problem, in 1911 Carty organized a special Research Branch of the Western Electric Engineering Department, with E. H. Colpitts as its head.[13]

The solution to this problem of long-distance transmission emerged from a new alliance of corporate interests and the latest academic science. Carty gave technical responsibility for the transcontinental line to a young physicist, Frank Baldwin Jewett. Jewett came to Western Electric in 1904 from a stint as an instructor in electrical engineering at MIT. He had earned

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Continuous Wave: Technology and American Radio, 1900–1932 (Princeton, 1985), 75–78. Lillan Hoddeson, in "The Emergence of Basic Research in the Bell Telephone System, 1875–1915," *Technology and Culture* 22 (1981): 530, notes that the term "fundamental research" began to appear in the company's rhetoric about 1907, a point echoed in Horace Coon, *American Tel and Tel: The Story of a Great Monopoly* (New York, 1939), 197. See also Reich, "Industrial Research" and *The Making of American Industrial Research*, for the defensive stance of early industrial research.

[11] Bancroft Gherardi, "The Dean of Telephone Engineers," *Bell Laboratories Record* 9 (September 1930).

[12] Mechanical telephone repeaters, logical extensions of simple and common telegraph repeaters, had existed for some time. These devices coupled acoustic energy from a speaker into a microphone, amplified the signal, and retransmitted it. This approach amounted to connecting two telephone circuits end to end, and numerous such devices were patented before 1900. More elegant solutions used the same principle but combined the elements into a single unit. Because of inertia, the mechanical coupling lagged the electrical signal and the output was not very linear with input, which meant that mechanical repeaters introduced significant distortion. No more than a few could be connected in series, and the delicate devices proved especially sensitive to temperature variations. Developing a repeater had a strategic dimension as well: the rapid rise of new wireless communications seemed a threat to wired communication, and repeaters would give the company the opportunity to control radio technology, which required similar types of amplifiers. Shaw (n. 6 above) reprints Carty's original proposal for the transcontinental line.

[13] The organization charts of the AT&T/Western Electric Engineering departments in 1905, 1907, 1909, 1911, 1915, and 1925 are reprinted in Shaw (n. 6 above), 400–406, and Fagan, 43–55.

his doctorate in physics at the University of Chicago, where he worked under Albert A. Michelson and became friendly with Robert Millikan. In 1910, faced with the problem of making repeaters for the transcontinental line, Jewett imagined that a solution, "in order to follow all of the minute modulations of the human voice, must be practically inertialess."[14] Mechanical repeaters had existed for some time, but they were impracticable because the inertia of their elements introduced significant distortion. Jewett thought the secret to "inertialess," and hence high-quality, repeaters lay in the electron physics he had studied at Chicago. At his request, Millikan sent several recent Ph.D.'s to AT&T to work on the project, and they formed an important axis of the company's research for years to come. In the ensuing decades Jewett would become an important figure in American science, but within AT&T his name was intimately associated with long distance transmission. When he retired in 1944, Bell Laboratories published an "implicitly biographical" tribute: not a description of the man's life, but a detailed technical history of the transcontinental line.[15]

After Jewett, Harold D. Arnold was the first of the Chicago group to arrive at AT&T, where he joined Colpitts's new Research Branch. Arnold, with fellow Millikan disciple H. J. van der Bijl, analyzed electron behavior within De Forest's audion tubes, characterized the tubes' behavior as circuit elements, and engineered them for mass, interchangeable production. By 1913, Arnold's "high vacuum thermionic tube," later known simply as the vacuum tube, could amplify signals in telephone repeaters.[16] This electronic repeater made possible the transcontinental line, which opened at the Pan American Exposition in San Francisco in 1915 with great fanfare. From the east coast, Alexander Graham Bell repeated his famous first conversation with Thomas Watson, now in California. Vail and President Woodrow Wilson both chimed in as well. The line consisted of 130,000 poles, more than 99 percent on open wire (the few cables forded streams and rivers). It had loading coils every eight miles and eight vacuum-tube repeaters ampli-

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[14] Jewett to Millikan, quoted in Fagan, 258. Jewett and Millikan had boarded together at Chicago, and Jewett was the best man at Millikan's wedding. Robert A. Millikan, *The Autobiography of Robert A. Millikan* (New York, 1950), 52–53. Millikan recounts the story of Jewett's approach to him, 116–17. Millikan remained a consultant in long-distance telephony, and his testimony helped settle the protracted suit between General Electric and AT&T over the vacuum tube, 120–22.

[15] Shaw, 533. Bruno Latour uses Jewett's appropriation of the electron as an example of "machines" as abstract apparatuses for tying together interested groups; *Science in Action* (Cambridge, 1987), 125–26.

[16] Shaw, 375, 379–82. Hugh Aitken argues that Arnold simply had a fundamentally different vision of the audion's potential than did De Forest. "Arnold . . . saw in it . . . something its inventor did not see: the possibility of making it into a high-vacuum device, operating by pure electron emission," whereas De Forest saw it as a gas-discharge device. Still, in Aitken's view, the distance between telephony and wireless delayed the Bell system's adoption of the audion for a number of years. Aitken (n. 10 above), 546.

fying the signal in both directions. Still, calling across country was far from routine; a three-minute call cost more than twenty dollars, and delivered only a third of the bandwidth of standard lines, which meant greatly reduced quality.[17] Its scratchy tone notwithstanding, the transcontinental line brought the entire country within the scope of Vail's unifying vision.

Amid the fanfare, however, the transcontinental line also marked a less-noted but equally critical technical and conceptual shift: the network became a machine. No longer was the network a passive device; with repeater amplifiers, the network actively added energy along the route, a significant change because it effectively decoupled the wave that represented the conversation from its physical embodiment in the cable. Electricity was no longer the conversation itself, but "useful only as a means of transmitting intelligible sounds . . . [with] no appreciable value purely from the power standpoint."[18] In other words, a working amplifier could renew the signal at any point, and hence maintain it through complicated manipulations, making possible long strings of filters, modulators, and transmission lines. Electricity in the wires became merely a carrier of messages, not a source of power, and hence opened the door to new ways of thinking about communications.

Standardization accompanied the conceptual shift. Once voices became signals, they could be measured and specified. No longer did the system merely deliver conversations according to some vague notion of clarity. Now the telephone company delivered products: signals within a specific frequency range, at a specified volume, and with a specified amount of noise. This transformation required standard measures: the "mile of standard cable," for example, became the "transmission unit," renamed the "bell," and eventually standardized in the "decibel," smaller by a factor of ten (and still today the standard measure of attenuation). Noise itself became a measurable quantity (based on thermodynamics), and the limiting factor in quality.[19] The message was no longer the medium, now it was a signal that could be understood and manipulated on its own terms, independent of its physical embodiment.

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[17] E. H. Colpitts, "Dr. H. D. Arnold," *Bell Laboratories Record* 6 (June 1928): 411–13. Actually, mechanical repeaters initially carried the transcontinental line but were quickly replaced with electronic ones. Gradually, more repeaters were added and the number of loading coils reduced; the coils reduced the bandwidth of transmission, and also reduced the speed of signal propagation, which led to problems with echoes. Shaw, 389–92, provides a detailed technical description of the transcontinental line. The line was not permanent but rather was "built up by switches" when needed, as was the New York/Denver line. Fagan (n. 9 above), 263–64.

[18] H. H. Nance and O. B. Jacobs, "Transmission Features of Transcontinental Telephony," *Journal of the American Institute of Electrical Engineers* 45 (1926): 1062.

[19] W. H. Martin, "Transmitted Frequency Range for Telephone Message Circuits," *Bell System Technical Journal* 9 (July 1930): 483–86, and "The Transmission Unit and Telephone Transmission Reference Systems," *Bell System Technical Journal* 3 (July 1924):

A Signal Organization

The success of the transcontinental line proved to Carty and AT&T the value of Jewett's alliance of physics, electronics, and telephone engineering.[20] Duplicating this success in other arenas, however, would require an organizational solidity as well. On 1 January 1925, the AT&T and Western Electric engineering departments combined to form the Bell Telephone Laboratories Incorporated (BTL). The new entity was responsible to AT&T for fundamental research and to Western Electric for the products of research, and the two companies funded it accordingly. Located at 463 West Street in Manhattan, the lab had thirty-six hundred employees, including two thousand scientists and engineers. Carty served as chairman of the board, which also included vice presidents of Western Electric and AT&T. Frank Jewett became president, and Harold Arnold director of research.

While an important milestone for corporate research, it is easy to overestimate the importance of the foundation of the laboratory itself. The new organization resembled the old Western Electric engineering department with only moderate changes.[21] Research conducted at Western Electric carried on largely unaltered, as did the careers of the engineers. Indeed, it would be inaccurate to characterize all of BTL's work as industrial research addressing fundamental scientific problems. Most of the staff of BTL, including Harold Black, engaged in the creative, if routine, work of designing telephone equipment and making it work. Despite the system-oriented organization, no group within BTL did "system engineering" in the post–World War II sense. The systems development department, to which Black belonged, did not formulate an abstract vision of the system overall, but in fact designed the actual circuits for the network, including equipment structures, office layouts, and the electric power systems required to run the equipment.[22]

Only the research department performed fundamental industrial research in the classical sense. Headed by Harold Arnold and comprising five hundred people, its mission was "to find and formulate broadly the

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400–408. R. V. L. Hartley, "TU Becomes 'Decibel,'" *Bell Laboratories Record* 7 (December 1928): 137–39. J. B. Johnson, "Thermal Agitation of Electricity in Conductors," and H. Nyquist, "Thermal Agitation of Electric Charge in Conductors," *Physical Review* 32 (1928): 97–113.

[20] The transcontinental line so solidified the alliance technically that loading coils were gradually removed from the network. The transcontinental line was fully unloaded in 1920, more than tripling the velocity of transmission, which reduced echo effects and improved the "sense of nearness" of the speakers. Shaw (n. 6 above), 396.

[21] Fagan, 54–55, compares BTL with the old AT&T and Western Electric engineering organizations. Also see the organization charts in Shaw, 406, for its similarity to the initial BTL organization outlined below.

[22] Paul B. Findley, "The Systems Development Department," *Bell Laboratories Record* 2 (April 1926): 69–73.

laws of nature, and to be concerned with apparatus only insofar as it serves to determine these laws or to illustrate their application in the service of the Bell System." Research covered nine main areas: speech, hearing, conversion of energy between acoustic and electric systems (speakers and microphones), electric transmission of intelligence, magnetism, electronic physics, electromagnetic radiation, optics, and chemistry.[23] Yet even within the Bell System, the research department did not have a monopoly on fundamental exploration, because the development and research (D&R) department of AT&T, with a similar charter and eleven hundred engineers and scientists, remained separate from BTL for the labs' first ten years. The negative-feedback amplifier emerged from interactions, and even conflicts, between the concrete, technical culture of systems development and the more theoretical research world growing within BTL.

The Technical Charge of Bell Labs

After the New York to San Francisco line in 1915, wires couldn't go much further (crossing the oceans was considered a problem for radio). But it was one thing to span the continent and quite another to offer high-capacity, economical service over that distance. Just keeping up with growing demand proved a constant problem: the Bell System added eight hundred thousand new subscribers in 1925 alone. Such expansion entailed planning and forecasting future requirements based on the rate of growth and detailed cost analysis to determine when new technologies were required.[24] Engineering studies evaluated a series of tradeoffs between the diameter of the wire, the number of repeaters, the cost of the terminal equipment, and the number of available channels. Increasing the capacity over existing long-distance routes, and thereby cutting costs, began to drive transmission development at Bell Laboratories.

Bell Labs engineers thus turned their attention to putting more conversations onto a single line. The most promising method, carrier multiplexing, modulated several voice signals onto high-frequency carrier signals. If these modulations occur in distinct frequency bands they can all travel over the same line, in much the same way that separate radio stations occupy the single electromagnetic spectrum (indeed, the technique became known as "wired wireless").[25] At the receiving end, a wave filter separates out the

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[23] Paul B. Findley, "The Research Department," *Bell Laboratories Record* 2 (June 1926): 164–70.

[24] H. P. Charlesworth, "General Engineering Problems of the Bell System," *Bell System Technical Journal* 4 (October 1925), 515–41.

[25] John Stone Stone, "The Practical Aspects of the Propagation of High Frequency Electric Waves Along Wires," *Journal of the Franklin Institute* 174 (October 1912), described high-frequency multiplex telephony as "identical with that of the new continuous wave train" radio, and included the Alexanderson alternator as an element of a tele-

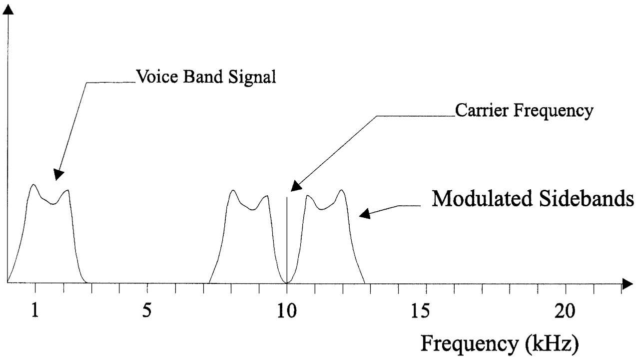

FIG. 1 Spectrum of a voice-band signal modulated onto a carrier.

voice channel (figs. 1 and 2). The idea had been around for a long time: both Elisha Gray and Alexander Graham Bell had investigated carrier techniques in their telephone research.[26] But vacuum tubes made carrier telephony practicable by allowing signals to be cleanly modulated, filtered, and amplified. The first commercial carrier system, type A, was installed in 1918, putting four two-way channels on open-wire pairs.[27] Still, carrier had its problems: because of the high frequencies, carrier signals faced greater attenuation than traditional voice-band signals and hence required more repeaters.

Another means of increasing capacity was transmission through cables, carrying ten times as many circuits as open wires but at the cost of high attenuation. In October 1925 a cable opened between New York and Chicago, but with delicate and precise construction pushing the limits of the medium. Success came at great cost in machinery and material, requiring an expensive, low-resistance cable and extensive loading and repeater equipment.[28] Making long cables practicable and economical required numerous repeaters and vast numbers of technicians distributed along the route to maintain the delicate devices. A simple comparison clarifies the difficulties of both carrier and cable transmission: the original (open-wire)

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phone design. Also see Lloyd Espenschied, "Application of Radio to Wire Transmission Engineering," *Bell System Technical Journal* 1 (October 1922) 117–41. On "wired wireless," see Fagan (n. 9 above), 282.

[26] E. H. Colpitts and O. B. Blackwell, "Carrier Current Telephony and Telegraphy," *Journal of the American Institute of Electrical Engineers* 40 (1921): 301–15, has a detailed history of carrier methods in telephony, as well as an elegant explanation of carrier modulation and transmission.

[27] In 1924 the type C system went into service, incorporating lessons from the more experimental A and B systems. Type C carrier systems were so successful the last one was not removed from service until 1980. O'Neill (n. 2 above), 3–14.

[28] See Charlesworth.

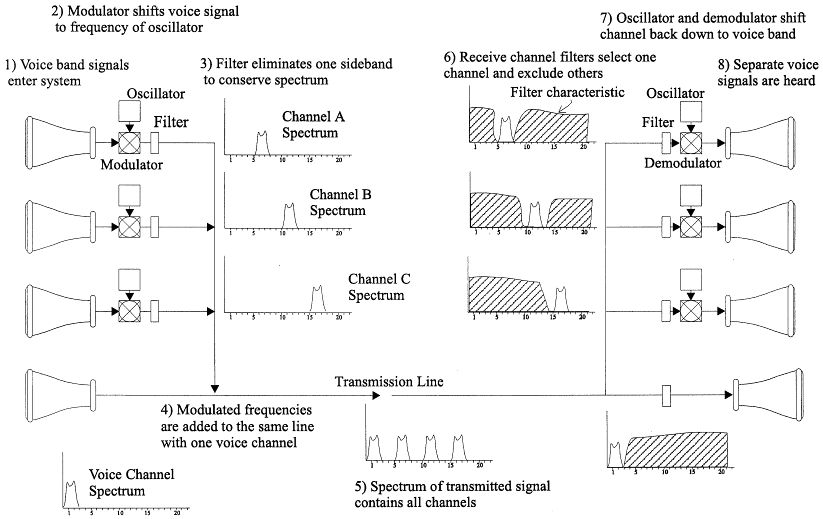

FIG. 2 Carrier modulation.

transcontinental line used fewer than ten repeaters across the continent; a carrier system over the same distance needed forty, a cable would require two hundred, and carrier and cables combined would need even more.[29] Hence carrier and cable transmission required amplifiers of extremely high quality.

An ideal amplifier is a pure multiplier, taking an input signal and multiplying it by some number (called *gain*) to produce an output. In other words, a perfect amplifier has a linear relationship between input and output. On a graph of output versus input, the amplifier's response is literally a straight line whose slope is the gain (it might also have a frequency dependent time delay, called *phase shift*, which is measured as an angle between input and output sine waves). For a vacuum tube, however, the output versus input curve tends to be more S-shaped (fig. 3). This nonlinearity introduces distortion and causes two problems. First, if the signal is modulated on a carrier the nonlinearity produces extraneous harmonics outside of the desired signal band. This becomes a problem with several signals carrier-modulated onto the same wire. The harmonics from one channel overlap the bands of others, causing cross talk—one conversation bleeding through into another (fig. 4). Second, since each amplifier adds a little distortion, a long line with numerous repeaters can garble the speech beyond recognition. Thus, for BTL, as the line became longer and longer, and as more and more signals squeezed onto a single wire, the amplifiers

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[29] O'Neill, 63, table.

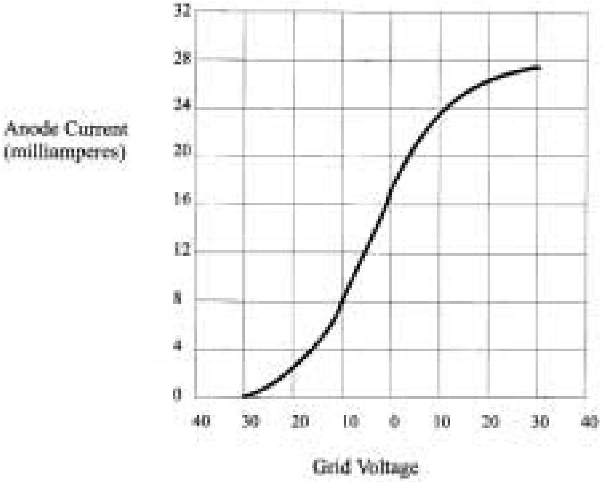

FIG. 3 Typical vacuum-tube nonlinearity. The output anode current is not a linear function of the input grid voltage.

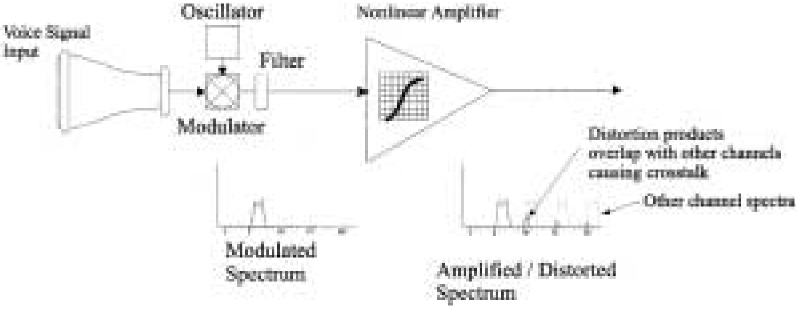

FIG. 4 Nonlinear amplifier causing distortion and cross talk in a carrier system.

had to become correspondingly higher in quality. This problem became a high priority for Bell Labs at its founding.

The Search for a Linear Amplifier

The first approach was to make the vacuum tubes themselves more linear. It was to this problem that Harold Black turned his attention when he joined the systems development department of Western Electric in 1921. A Massachusetts native, he had graduated that year from Worcester Polytechnic Institute in electrical engineering. At Western Electric Black worked with Mervin Kelley and the vacuum-tube department, but with little success. Vacuum tubes, despite their utility as circuit elements, remained subtle, unruly—and nonlinear—devices (hence Kelley's efforts, years later, overseeing the development of the transistor).[30]

Black began to rethink the problem in terms of signals. He conceptualized the output of the amplifier as containing a pure, wanted component, the signal, and an impure, unwanted component, the distortion. The problem, then, was to somehow separate the two and keep only the pure signal. He came up with a clear, if inelegant, solution: a "feed-forward" amplifier that generated a copy of its own distortion and subtracted it from the output signal. Black built a laboratory prototype that achieved the desired result, and he applied for a patent in 1925.[31] Though this setup proved that a low-distortion amplifier was possible, it was far from practicable. Black's overly complex new amplifier required careful attention and continuous adjustment, which engineers could do in a testing lab but not for a system deployed in the field.

STABILIZING BLACK'S BOX

For three years Black struggled to simplify his solution. Finally, in 1927, he had the epiphany on the ferry: if the gain of the amplifier were reduced by some amount, and that amount fed back into the input, the linearity could be greatly improved. In fact, distortion was reduced (that is, linearity improved) by the same factor by which the gain was reduced. Black published a simple explanation of the idea in a 1934 paper (fig. 5), showing that the gain of the amplifier depends primarily on the feedback network, ß, and not on the gain, μ, of the amplifier itself.[32] The feedback network can consist of only passive elements, such as resistors, capacitors, and inductors, that are both more linear than vacuum tubes and more stable with respect to temperature and other changes over time. Consider an example: a feedback amplifier with a vacuum-tube gain of 100,000 is enclosed in a feedback loop that reduces its gain to 1,000. The linearity of the amplifier overall thus increases by a factor of 100, an incredible improvement. The price, of course, is to throw gain away and settle for a much reduced level of amplification. On 29 December 1927, Black and BTL engineers succeeded in making a feedback amplifier whose distortion was reduced by a factor of 100,000 (and whose gain was reduced accordingly).[33]

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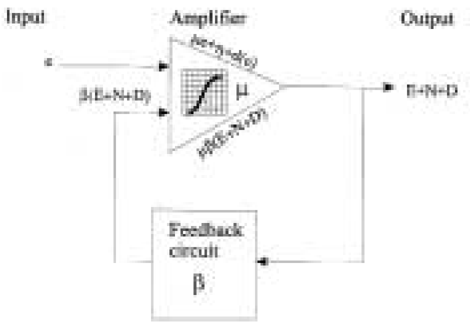
[30] This account is based on Black, "Inventing the Negative Feedback Amplifier" (n. 1 above), and Harold S. Black to A. C. Dickieson, 16 June 1974, AT&T archives, Warren, N.J. For a typical effort to design linear vacuum-tube amplifiers, see E. W. Kellogg, "Design of Non-Distorting Power Amplifiers," *Electrical Engineering* 44 (1925): 490.

[31] Harold S. Black, U.S. Patent No. 1,686,792, "Translating System."

[32] This assumption holds to within $1/\mu$, so if the amplifier gain is 100, then 1 percent of the gain is determined by the vacuum tube and 99 percent by the feedback network.

[33] Black, "Inventing the Negative Feedback Amplifier."



Amplifier System with Feedback

ε Signal input voltage
μ Propagation of amplifier circuit [gain]
με Signal output voltage without feedback
η Noise output voltage without feedback
d(E) Distortion output voltage without feedback
β Propagation of feedback circuit
E Signal output voltage with feedback
N Noise output voltage with feedback
D Distortion output voltage with feedback

The output voltage with feedback is E+N+D and is the sum of με+η+d(E), the value without feedback plus μβ(E+N+D) due to feedback.

$$E+N+D=\mu\varepsilon+\eta+d(E)+\mu\beta(E+N+D)$$

$$(E+N+D)(1-\mu\beta)=\mu\varepsilon+\eta+d(E)$$

$$E+N+D=\frac{\mu\varepsilon}{1-\mu\beta}+\frac{\eta}{1-\mu\beta}+\frac{d(E)}{1-\mu\beta}$$

$$\text{If } |\mu\beta| >> 1,\ E = -\varepsilon/\beta$$

Under this condition the amplification is independent of μ but does depend on β. Consequently the overall characteristic will be controlled by the feedback circuit which may include equalizers or other corrective networks.

FIG. 5 Harold Black's negative feedback amplifier. (Harold S. Black, "Stabilized Feedback Amplifiers," *Bell System Technical Journal* 13 [January 1934]: 3.)

Still, Black had no easy time convincing others at Bell Labs of the utility of his idea. He recalled that Jewett supported him, but that the director of research, Harold Arnold, refused to accept a negative-feedback amplifier and directed Black to design conventional amplifiers instead.[34] Black had similar difficulties with the U. S. Patent Office. His application for a "Wave Translation System," originally filed in 1928, was not granted until 1937.[35] To a generation of engineers who had struggled to make the vacuum tube amplify at all, throwing away the hard-won gain seemed absurd.

More important, no one could understand how an amplifier's output could be fed back to its input without a progressive, divergent series of oscillations. Bell engineers at the time found it difficult to make a high-gain amplifier *without* feedback. Subtle, uncontrolled feedback paths would arise through unintentional effects such as stray capacitance between wires, or even between elements within the tube itself, and cause the amplifier to go into "parasitic oscillation" or "singing" (much like the whistling in a

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[34] Ibid., 59–60.

[35] Black to Dickieson; Harold S. Black, patent application 298,155, 8 August 1928; "File History of Black Application Serial No. 298,155," AT&T archives.

poorly tuned public address system). In 1924, for example, two BTL engineers, H. T. Friis and A. G. Jensen, studied what they called "feed-back or regeneration" as it occurred through a tube, noting that it "makes the total amplification vary irregularly in a very undesirable manner and also makes the set 'sing' at certain frequencies."[36] Black's work went against the grain for experienced amplifier designers: they sought to eliminate feedback, not to incorporate it.

Black interpreted the resistance to his ideas as evidence of their radical nature. Yet he was an engineer with a bachelor's degree in the systems department; he did not possess the analytical sophistication, the communications skills, or the prestige of the research scientists at BTL. His lab assistant during this period, Alton C. Dickieson, recalled Black as clashing constantly with his own management and the rest of BTL. Dickieson's recollections of Black's troubles parallel the inventor's own accounts, so his memory seems credible.[37] Such conflicts were one thing for a lucid genius, but Black was far from eloquent. "A compulsive, non-stop talker," Dickieson recalled, Black "was inventive and intuitive, but not particularly clear at exposition." His negative-feedback circuit was only the latest in a series of attempts over a period of several years, all of which Dickieson wired up and built, but, as he recalled, "none of the schemes we tried showed any real promise." Dickieson also remembered "quite a bit of rivalry" between the Ph.D.-trained researchers and the systems people. "There seemed to be some feeling that *exploratory* development was the exclusive province of the research people. Mathematicians such as Thornton Fry [head of BTL's math department] found Black's mathematics beneath contempt."[38] Black—restless, creative, and a bit arrogant—was traversing the established boundaries of the organization, and running headlong into the cultural differences between the research department and his own lower-status systems department.

Credible as Dickieson's recollections seem, no contemporary accounts exist to support or refute them. The documents do allow, however, a thorough analysis of Black's ideas, and how Black himself had to transform them (and enlist others to transform them) in order to win their acceptance. A key point involves his claim that the epiphany on the ferry included a concern for dynamic stability, that if he "kept the device from oscillating (singing, as we called it then)" it would work. He implies that he understood "stability" of the amplifier as the central problem. But a look at

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[36] H. T. Friis and A. G. Jensen, "High Frequency Amplifiers," *Bell System Technical Journal* 3 (April 1924).

[37] See, for example, Black, "Inventing the Negative Feedback Amplifier" (n. 1 above) 59–60, for Black's conflict with H. D. Arnold and intimations of constant friction with his superiors.

[38] A. C. Dickieson to M. J. Kelley, 6 July 1972, AT&T archives, 43 09 03. Emphasis added.

Black's conception of stability at the time reveals it to be different from the standard meaning of freedom from oscillation. In fact, Black's conceptions of both negative feedback and stability differed markedly from those of much of the engineering community at the time, although they would have been familiar to engineers working on the telephone network.

TWO CULTURES OF FEEDBACK AND STABILITY

Today the "negative" in negative-feedback amplifiers means that the feedback signal subtracts from the input signal rather than adding to it (that is, the sign of the feedback signal is reversed). James Watt's flyball governor on a steam engine offers an analogy: when the engine speeds up, the spinning balls slow it down; when the balls spin slower, they speed up the engine. Hence the feedback is negative.

In Black's time, however, the definition of this specific-sounding term, "negative feedback," had yet to be settled. The idea of positive feedback had become current in the 1920s with the introduction of the regenerative amplifier. Positive feedback, or regeneration, in a radio amplifier increased the sensitivity of a receiving tube by sending a wave back through an amplifier many times. Black insisted that his negative feedback referred to the opposite of regeneration: gain was reduced, not increased. Yet, to return to the analogy of the steam engine governor, Black's use of "negative" means the energy required to spin the balls reduces the energy output of the engine, not that the balls trigger an action that slows it—hardly a significant effect for a steam engine. In their 1924 paper Friis and Jensen had made the same distinction Black had between positive feedback and negative feedback, that is, distinguishing one from the other not by the sign of the feedback itself but rather by its effect on the amplifier's gain.[39] In contrast, Nyquist and Bode, when they built on Black's work, referred to negative feedback as that with the sign reversed. Black had trouble convincing others of the utility of his invention in part because confusion existed over basic matters of definition.

Misunderstanding also arose over the critical idea of stability. Dickieson recalled why those concerned with singing in amplifiers did not take Black seriously: "Harold did not even approach the question of stability—he simply assumed that it did not sing."[40] Actually, Black was deeply concerned with stability: his first published paper on the amplifier appeared in 1934 with the title, "Stabilized Feedback Amplifiers." But to Black "stability" referred not to freedom from oscillation but to the long-term behavior of components in the telephone network.[41] Life in the network exposed a tele-

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[39] Friis and Jensen, 204.

[40] Dickieson to Kelley.

[41] "When many amplifiers are worked in tandem . . . it becomes difficult to keep the overall circuit efficiency constant, variations in battery potentials and currents, small when considered individually, adding up to produce serious transmission changes in the overall circuit"; Harold S. Black, "Stabilized Feedback Amplifiers," *Bell System Technical*

phone repeater to a harsh world, and Black sought to insulate the signal from brutal reality. He wanted to use feedback to stabilize the characteristics of the amplifier over time. Temperature changes, aging of components, changes in the power supply, and any number of other factors could affect the performance of an amplifier. Rain and temperature fluctuations, for instance, changed the resistance of the wire and caused significant variations in attenuation, sometimes by a factor of a hundred or more over the course of a single day, and to comparable degree across the change of seasons.[42] These fluctuations could greatly alter the physics of transmission, a potentially disastrous effect for systems operating close to their physical limits.

Yet to the scientifically trained engineers at BTL, stability, in the sense of freedom from oscillation, was the main difficulty of the feedback amplifier. Homer Dudley, discussing Black's paper in the journal *Electrical Engineering*, listed freedom from singing as one of the two most important problems for the amplifier.[43] Yet this type of stability was not Black's concern. His original patent application, filed in 1928, makes no mention of even the possibility of singing or oscillation.[44] When resubmitting the application in 1932, he added this clarification: "Another difficulty in amplifier operation is instability, not used here as meaning the singing tendency, but rather signifying constancy of operation as an amplifier with changes in battery voltages, temperature, apparatus changes including changes in tubes, aging, and kindred causes . . . Applicant has discovered that the stability of operation of an amplifier can be greatly improved by the use of negative feedback."[45] Black even acknowledges the other meaning of stability, but assigns it unequivocal second billing: "Applicant uses negative feedback for a purpose quite different from that of the *prior art* which was to prevent self-oscillation or 'singing.' To make this clearer, applicant's invention is not concerned, *except in a very secondary way* . . . with the singing tendency of a circuit. Its primary response has no relation to the phenomena of self-oscillation" (emphasis added).[46] In the patent, Black "simply assumed" that the amplifier did not oscillate.

Journal 13 (January 1934). This paper was presented at the winter convention of the American Institute of Electrical Engineers, New York, January 1934, and also published in *Electrical Engineering* 53 (January 1934): 114–20. See also the discussions of the paper in *Electrical Engineering* by F. A. Cowan (April 1934): 590; G. Ireland and H. W. Dudley (March 1934): 461–62; and H. Nyquist (September 1934): 1311–12.

[42] H. A. Affel, C. S. Demarest, and C. W. Green, "Carrier Systems on Long Distance Telephone Lines," *Bell System Technical Journal* 7 (July 1928): 384. Green was Harold Black's boss.

[43] Dudley, discussion of Black, "Stabilized Feedback Amplifiers."

[44] Harold S. Black, patent application 298,155; "File History of Black Application Serial No. 298, 155" AT&T archives.

[45] Harold S. Black, U.S. Patent No. 2,102,671, "Wave Translation System," 2.

[46] Ibid.

Black's conception of stability, strange as it may seem, derived from his position in the systems development department as opposed to the research department. Where a researcher might focus on the theoretical behavior of the system, Black was concerned with its concrete, daily characteristics. To system engineers such as Black, "stable" amplifiers were those that retained consistent performance in the face of the varying conditions experienced by equipment in the telephone network. Consistency, regularity, and stability of the circuit elements were critical to transmission systems. Black employed this operational conception of stability in the analysis of his amplifier. He used the term stability as an engineer who saw the system as a concrete, operational entity, not as one who thought in abstract diagrams.

Nevertheless, system engineers, despite their emphasis on transmission stability, should also have been familiar with dynamic stability. Repeater amplifiers had always had problems with singing; they would sing if the signal from one direction of transmission leaked into the other (a full repeater requires two amplifiers, one for each direction of transmission). In response to these problems, telephone engineers filtered out the singing frequencies and limited the amount of gain in each repeater. Carrier systems also tended to sing, either locally or through the transmission line.[47] The now familiar telephone handset, introduced in the late 1920s, depended on understanding and preventing the singing or "howling" that resulted from the mouthpiece picking up sound from the earpiece.[48] Moreover, the stability of motion had been a popular topic in physics in the late nineteenth century, and at least some telephone engineers in the 1920s were aware of it, although they were unsure of its relevance to vacuum-tube circuits.[49]

Multiple, overlapping conceptions of negative feedback and stability thus surrounded the introduction of Black's amplifier. The Bell Laboratories research culture was not monolithic, but rather comprised at least two engineering subcultures: Ph.D.-level mathematicians and scientists interested in fundamental questions, and system engineers such as Black,

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[47] In 1921, for example, Colpitts and Blackwell wrote that singing in a carrier system could arise when the gain was greater than one and when there existed "sufficient unbalance" between the circuits. Colpitts and Blackwell (n. 26 above), 313.

[48] In 1926 Harvey Fletcher analyzed the howling telephone as a dynamic electrical system to understand the relationship between impedance, frequency, and the tendency to break into the oscillation; "The Theory of the Operation of the Howling Telephone with Experimental Confirmation," *Bell System Technical Journal* 5 (January 1926): 27–49. Fletcher's paper does not employ the terms "stability" or "feedback" in its analysis, although it does analyze electro-acoustic circuits that greatly resemble canonical feedback systems. Shaw (n. 6 above), 382–83. On the problems of handset howling, see Fagan (n. 9 above), 146–50.

[49] Bennett (n. 2 above), 77. See also Ronald M. Foster, "A Reactance Theorem," *Bell System Technical Journal* 3 (April 1924): 266.

concerned with building the network and keeping it running. Their differing backgrounds, and differing notions of ideas such as "stability," help explain why the research department did not take Black seriously. As Nyquist and Bode's contributions make clear, it would take both approaches to make the feedback amplifier a practical reality.

When Black invented the negative-feedback amplifier, he invented a different machine from both the one it eventually became and the one he remembered. Especially in light of his claim that he recognized feedback as a unifying principle across different types of systems, these clashing visions raise the question of whether Black drew on the long tradition of regulators and governors that preceded him.

SINGING AND HUNTING

Feedback techniques had of course been commonly used for a long time in governors, regulators, thermostats, automatic pilots, and numerous other devices. In his memoirs, Black said that he understood his feedback amplifier as part of that technological trajectory. The significance of the origin myth rests on Black's supposed recognition that negative feedback is isomorphic across diverse types of systems. Indeed, Black's patent, as issued, states that the negative-feedback principle applies to more than electronic amplifiers: "the invention is applicable to any kind of wave transmission such as electrical, mechanical, or acoustical . . . the terms used have been generic systems." But the patent never specifies what those other applications might be, and a steam-engine governor, an automatic pilot, or a servomechanism fit only loosely into the category "wave translation system" (the title of Black's patent). Black likely had in mind more directly analogous systems, such as the numerous electro-acoustic translations required in telephony. Neither the patent, nor any of Black's early writings, nor the writings of any of the BTL feedback theorists for at least ten years, mention regulators, governors, automatic pilots, or any of the myriad devices we now understand as employing negative feedback.

Nonetheless, such devices were themselves in wide use within the telephone network. Telephone repeaters needed regular adjustment as the characteristics of the transmission lines changed in response to environmental changes. In the late 1920s AT&T installed automatic regulators in about every fourth repeater station; these devices adjusted amplifier gain in response to a feedback loop that sensed the wire's characteristics. In 1929, for example, the New York/Chicago line included six regulating stations among its twenty repeaters.[50] In this light, Black's stability of transmission was a kind of automation: his stable feedback amplifiers relieved network maintenance personnel of the task of adjusting the delicate amplifiers.[51]

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[50] E. D. Johnson, "Transmission Regulating System for Toll Cables," *Bell Laboratories Record* 7 (January 1929): 183–87.

[51] Ireland (n. 41 above).

Regulators and governors could also be found within BTL's engineering culture. Sound movies, for example, required tight control lest variations in film speed change the pitch of the sound and become annoying to the viewer. Similarly, early television systems in development at BTL in the 1920s employed large mechanical disks to scan the picture (instead of the later electron beams). Keeping these disks exactly aligned required precise regulators. In a series of papers published between 1927 and 1929, Hugh Stoller of the apparatus department explicitly compared his speed controls to steam engine governors and even discussed the phenomenon of "hunting," equivalent to singing in an amplifier.[52] He included a drawing of a flyball governor in the *Bell Laboratories Record*, and used "stability" in the sense of freedom from oscillation. Stoller even used the term "feed back" for the electrical speed regulation in his own circuits.[53] Had Black looked, he would have found discussion of traditional mechanical regulators in his own organization and its publications

In fact, the analogy between a mechanical regulator and an electronic one would not have been a great leap for Black, as Stoller made the connection clearly but without much fanfare. But Black did not take that step. He did not see his negative-feedback amplifier as analogous to regulators and governors and he did not see hunting in those devices as comparable to singing in an amplifier.

This critical look at Black's conception of his amplifier provides some perspective on the origin myth. Black's flash of insight, however much it enlightened him on the structure of negative feedback, did not give him an artifact he could sell, nor did it give him the modern conception of a negative-feedback amplifier or a broadly applicable notion of feedback. But it would be wrong to suggest that Black would have found a more receptive audience for his invention had he realized that the amplifier's stability was a key problem, that negative feedback worked similarly to regulation, that singing resembled hunting. These judgments we can only make with hindsight. The important historical point must be made positively: to Black the amplifier was a means of throwing away gain to achieve linearity in a vacuum tube, a way of stabilizing the repeaters in the telephone system subject to variation and hazard. On these points he was always clear, consistent, and determined.

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[52] Hugh M. Stoller, "Synchronization and Speed Control of Synchronized Sound Pictures," *Bell System Technical Journal* 8 (January 1929): 184–95. Also see H. M. Stoller and E. R. Morton, "Synchronization of Television," *Bell System Technical Journal* 6 (October 1927): 604–15, and H. M. Stoller "Speed Control for the Sound-Picture System," *Bell Laboratories Record* 7 (November 1928): 101–5. W. Trinks, *Governors and the Governing of Prime Movers* (New York, 1919).

[53] H. M. Stoller, "Speed Control for the Sound-Picture System," *Bell Laboratories Record* 7 (November 1928): 101–5. Stoller also published on voltage regulators; H. M. Stoller and J. R. Power, "A Precision Regulator for Alternating Voltage," *Transactions of the American Institute of Electrical Engineers* 48 (1929): 808–11.

In his 1934 paper "Stabilized Feedback Amplifiers," Black presented his amplifier to the world. He attributed the delay from his 1927 insight to the 1934 paper to corporate secrecy, but that can account for at most five of the seven years. Black's paper, in fact, was not the first word from the telephone company on the negative-feedback amplifier; that word, a paper that Black cited and discussed, had appeared two years earlier. It was the work of an ally, to whom Black had turned for help, but who remade Black's box. Harry Nyquist rethought negative feedback by redefining stability.

DIAGRAMMING STABILITY

Harry Nyquist, a Swedish immigrant with a Ph.D. in physics from Yale University, brought negative feedback from Black's curiosity into the network. Nyquist belonged not to BTL but to the development and research department of AT&T; he stabilized Black's box by bringing it into the frequency domain.[54]

In May 1928 Nyquist asked Black to join in developing a new carrier system and to include the negative-feedback amplifier in a demonstration of new transmission techniques. This project, known as the Morristown Trial, installed seventy-eight repeaters of Black's design spaced every twenty-five miles of cable. The cable folded back on itself, so all the amplifiers were located in the same laboratory in Morristown, New Jersey.[55] Before his work on the Morristown trial, Nyquist had worked on problems of both transmission stability and regulation.[56] With the Morristown trial, Nyquist brought this experience to amplifiers.

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[54] Hendrik W. Bode, "Harry Nyquist" (obit.), *IEEE Spectrum* 14 (April 1977).

[55] For a detailed account of the Morristown Trial, see A. B. Clark and B. W. Kenall, "Carrier in Cable," *Bell System Technical Journal* 12 (July 1933): 251–62; see also O'Neill (n. 2 above), chap. 5, "Carrier on Cable." Making the system work as planned proved no simple matter, but such was the purpose of an engineering trial. Repeater amplifiers did not pose the only problems: cable design (the number, size, and shielding of each of the many wire pairs) proved especially critical as well. Shielding, grounding, and interference between signals plagued the system. Because of the depression, AT&T changed its emphasis from new systems to improving capacity with the existing plant. Engineers at BTL had several years to refine the results of Morristown and to work on ways of compressing more transmission onto existing wires. The Morristown Trial formed the basis for the K-type carrier system, introduced in the late 1930s, which carried twelve voice channels on cables at frequencies from 12 to 50 kHz for distances up to 4,000 miles. K-carrier furnished 70 percent of the increased capacity in the country (which doubled from 1940 to 1947) and remained in service until at least 1980. K-carrier also included a pilot wire-transmission regulation scheme, with an automatic self-balancing regulator and a self-synchronizing motor. C. W. Green and E. I. Green, "A Carrier Telephone System for Toll Cables," *Bell System Technical Journal* 17 (January 1938).

[56] H. Nyquist, U.S. Patent No. 1,887,599, "Constant Current Regulation"; U.S. Patent No. 1,683,725, "Phase Regulating System." Applications filed in 1928 and 1926, respectively. B. P. Hamilton, H. Nyquist, M. B. Long, W. A. Phelps, "Voice-Frequency Carrier Telegraph System for Cables," *Transactions of the American Institute of Electrical Engineers* 44 (February 1925): 327–39. This paper (which erroneously gives Nyquist's first initial as

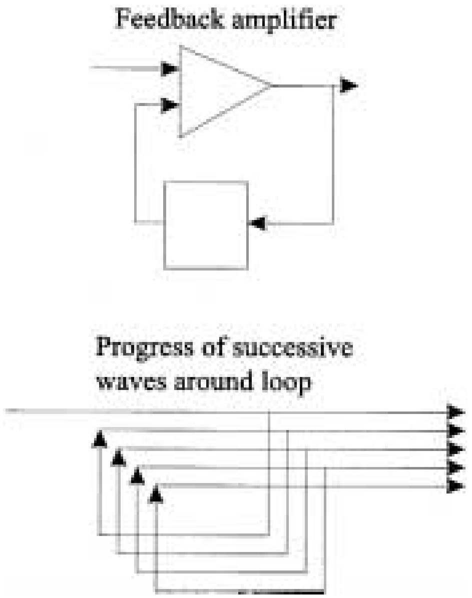

FIG. 6 "For the purpose of studying the singing condition, it is permissible to study the feedback condition as a series of waves. . . ." (H. Nyquist, discussion of a paper by H. S. Black, "Stabilized Feedback Amplifiers," *Electrical Engineering* 53 [September 1934], 1311.)

His 1932 paper, "Regeneration Theory," provided a rigorous set of measurable conditions by which to determine the stability of a feedback amplifier. He redefined feedback as a frequency-dependent phenomenon, and stability in terms of transient disturbances composed of different frequencies (essentially shocks to the system). "For the purpose of studying the singing condition," he wrote, "it is permissible to regard the feed-back phenomenon as a series of waves."[57] For Nyquist, if all disturbances die out after a finite period of time, the circuit is stable. If any disturbance goes on indefinitely, the circuit is unstable (fig. 6).[58] In light of this definition, it became clear to Nyquist that two conditions are necessary and sufficient to make an amplifier unstable and cause singing: first, if the wave coming around the feedback loop equals or exceeds in magnitude the input to the amplifier, that is, if the gain is equal to or greater than one; second, if the

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N.) also includes a discussion of the precision governor required for generating carrier frequencies for this telegraph system, suggesting that Nyquist had exposure to regulation before his 1932 paper on feedback, "Regeneration Theory," *Bell System Technical Journal* 11 (January 1932): 126–47.

[57] Nyquist, discussion of Black, "Stabilized Feedback Amplifiers" (n. 41 above).

[58] Nyquist, "Regeneration Theory"; Bennett (n. 2 above), 82–84.

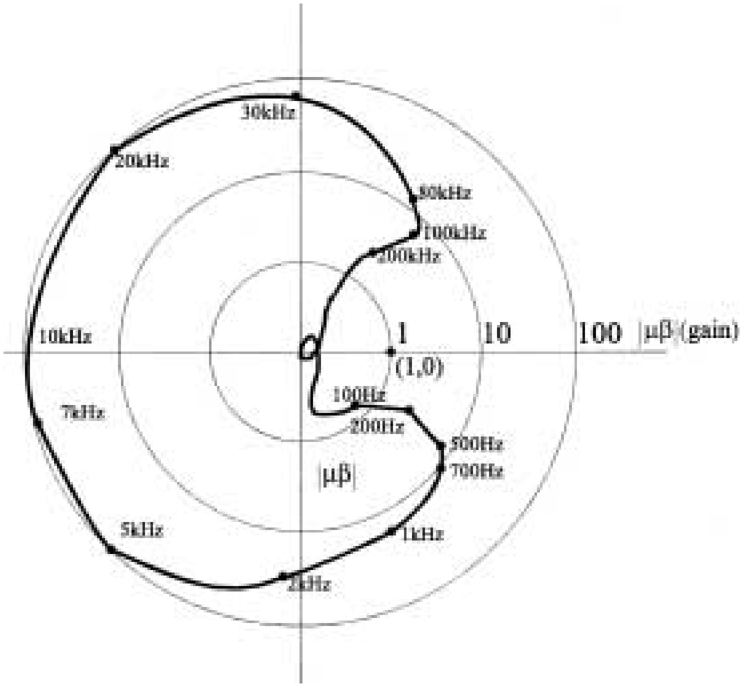

FIG. 7 Original-style Nyquist diagram, showing gain (magnitude) versus phase shift (angle) plotted for several different frequencies on a polar plot. Since the curve does not enclose the point (1,0), the system is stable. If curve did enclose that point, the system would be unstable. (After H. Bode, "Feedback: The History of an Idea," reprinted in *Selected Papers on Mathematical Trends in Control Theory*, ed. Richard Bellman [New York, 1964], 114.)

feedback wave is inverted compared to the input wave (that is, its phase shift is 180°). If these conditions are both met for any frequency, then the amplifier is unstable and will oscillate. Nyquist turned these conditions into a simple, empirical method for determining stability: open the loop, measure the amplifier's parameters (gain and phase shift) for varying frequencies, record them on a polar plot, and use the plot to graphically determine stability (fig. 7).[59] This plot became known as a "Nyquist diagram," and the

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[59] Nyquist's method was this: First, break the loop so the amplifier will not feed back on itself. Then measure its "open loop characteristics," plotting two easily measured quantities, gain and phase, against each other as they vary with the frequency of the input signal. If the resulting curve encloses the point that represents a unity gain and 180° shift, the system is unstable. If the point lies outside the curve, the system is stable. Nyquist, "Regeneration Theory." In 1934, BTL engineers compared Nyquist's criterion to Routh's test from his 1877 Adams Prize paper on stability in dynamic mechanical systems. They

test remains the "Nyquist stability criterion" or the "Nyquist criterion."[60] This technique reduced a significant amount of calculation to a simple procedure, a literary technology, and a tool for engineers to think with. It is still used today.

FEEDBACK AS A NETWORK PROBLEM

It remained for one more BTL engineer, Hendrik W. Bode, to complete telephony's prewar phase of feedback theory. Bode came to BTL in 1926, fresh from a master's degree at Ohio State, where had also done his undergraduate degree; he received a Ph.D. in physics from Columbia in 1935. Bode's expertise was not in feedback, nor even in amplifiers or vacuum tubes, but in the useful but esoteric *network theory*. The theory of electrical networks dealt not with the telephone network itself but with abstractions of the numerous small networks of resistance, capacitance, and inductance that determined its behavior.[61]

As the Bell System adopted carrier transmission and began to manipulate signals in the frequency domain, electrical networks became increasingly critical. Filter networks, for example, separated specific frequencies out of the spectrum, and equalizer networks compensated for the distortion in a transmission line. In 1934, Bode developed and published a general theory that accounted for all types of networks. Bode called this work "a sort of algebra" that allowed designers to manipulate network designs graphically, without solving their tangled equations.[62]

Bode's work on networks merged with feedback amplifiers because of yet another new transmission medium, coaxial cable, which had only one conductor surrounded by a conductive shield. These cables allowed several hundred conversations to be multiplexed together and could also carry the new broadband television signals. As with the jump from open wire to cable, the jump to coaxial cables placed heavier demands on repeaters, equalizers, and system performance overall.[63]

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found the two stability analyses compatible, and thus linked the new feedback theory to the older work on dynamic stability. Despite this link, however, their work makes no mention of applying feedback amplifier theory to other dynamic systems. E. Peterson, J. G. Kreer, and L. A. Ware, "Regeneration Theory and Experiment," *Bell System Technical Journal* 13 (October 1934): 680–700.

[60] Bennett, 83.

[61] S. Millman, ed., *A History of Engineering Science in the Bell System: Communications Sciences (1925–1980)* (Murray Hill, N.J., 1984), 16–17. Also see O'Neill (n. 2 above), 204–8. For a good summary of the work on network theory in the twenties and thirties, see Karl L. Wildes and Nilo A. Lindgren, *A Century of Electrical Engineering and Computer Science at MIT, 1882–1982* (Cambridge, 1985), chap. 9, "Network Analysis and Synthesis: Ernst A. Guillemin."

[62] H. W. Bode, "General Theory of Electric Wave Filters," *Journal of Mathematics and Physics* 13 (November 1934): 275–362.

[63] L. Espenschied and M. E. Strieby, "Systems for Wide-Band Transmission over

In 1934, Bode set about designing an equalizing network for a repeater amplifier for coaxial cable.[64] The trouble was, Bode had to design the equalizer network after the amplifier had already been designed, and such post hoc modification made the amplifier unstable. "I sweated over this problem for a long time without success," Bode recalled. Finally, "in desperation," he redesigned the entire amplifier using techniques from network theory. Where Nyquist had provided a way to determine if an existing amplifier was stable, Bode now aimed to design a stable amplifier to meet specified parameters for performance.

Bode's 1940 paper "Relations Between Attenuation and Phase in Feedback Amplifier Design," remains his best-known and most succinct contribution to feedback theory. The opening pages have a decidedly pessimistic tone, as Bode notes that the stability of a feedback amplifier "is always just around the corner." He begins: "The engineer who embarks upon the design of a feedback amplifier must be a creature of mixed emotions. On the one hand, he can rejoice in the improvements in the characteristics of the structure which feedback promises to secure him. On the other hand, he knows that unless he can finally adjust the phase and attenuation characteristics around the feedback loop so the amplifier will not spontaneously burst into uncontrollable singing, none of these advantages can be actually realized."[65]

Coaxial Lines," *Bell System Technical Journal* 13 (October 1934): 654–79. M. E. Strieby, "A Million-Cycle Telephone System," *Bell System Technical Journal* 16 (January 1937): 1–9. See also O'Neill, chap. 6, "Coaxial Cable," especially 131–39. The system Bode worked on became known as the L1; it was tested on a line from New York to Philadelphia in 1936–38 and put into service just before the war.

64. Here Bode came to a critical realization. The overall amplifier behaves like the *reciprocal* of its feedback elements—when the feedback path divides, for example, the amplifier overall multiplies, when the feedback element passes certain frequencies, the amplifier overall blocks those frequencies, and vice versa. A passive equalizer had to mimic the reciprocal of the transmission line to cancel out its effects. In network theory, however, creating the inverse of a physical network could be a complicated affair, and might not even be physically possible. Bode realized, however, that since the feedback amplifier inverted the behavior of the feedback network, the problem of equalizer design reduced to the simpler problem of designing a feedback network to simulate the transmission line exactly, rather than to invert it. H. W. Bode, "Variable Equalizers," *Bell System Technical Journal* 17 (April 1938): 229–44. Black wrote in 1934: "For many types of frequency characteristics it is difficult, and for some impossible, to construct a passive network having the exact inverse characteristic [as the transmission line]. With this type of [feedback] amplifier, however, it is only necessary to place in the feedback circuit apparatus possessing the same characteristic as that to be corrected." Black, "Stabilized Feedback Amplifiers" (n. 41 above), 294.

65. Bode, "Relations Between Attenuation and Phase in Feedback Amplifier Design" (n. 1 above). For other discussions of this paper, see Bennett (n. 2 above), 84–86; Millman, 29–30; O'Neill, 68–70. In later years, Bode displayed some aversion to Black's version of events. He wrote to A. C. Dickieson in 1974, after reviewing Black's account, that "this is not exactly how one ordinarily writes formal technical history [interestingly, Bode had some notion of 'formal technical history']. . . . Have you thought of a less personalized

Bode likens a feedback amplifier to a perpetual motion machine that would work "except for one little factor" that never quite goes away, despite all the tweaking.[66] Bode elucidates the parameters (gain and phase shift) "which impose limits to what can and cannot be done in a feedback design . . . and [forbid] the building of a perpetual motion machine." The price of using feedback, he continues, "turns out to be surprisingly high." It "places a burden on the designer," and without new tools "he is helpless." Bode seems to be addressing Black himself and his uncritical exuberance for the benefits of feedback, regardless of stability problems. "Unfortunately, the situation appears to be an inevitable one. The mathematical laws are inexorable."[67] Like Nyquist, Bode developed simple, graphical techniques to determine stability by plotting observed and analytic quantities. Like Nyquist diagrams, these graphs survive today as "Bode plots."

Nyquist's stability conditions produced an answer: the amplifier is stable or it is not. Bode's technique assessed how much stability it had, with quantitative measures. Bode also imposed limits on the possible performance of the feedback amplifier by proving that "we cannot obtain unconditionally stable amplifiers with as much feedback as we please" because too much feedback could make the amplifier unstable.[68] His name is permanently associated with feedback, but he always linked it to its network roots: "it is still the technique of an equalizer designer," he wrote in retrospect. "I can imagine that the situation may well seem baffling to someone without such a background."[69] The title of Bode's 1945 book *Network Theory and Feedback Amplifier Design* reflects his primary experience in networks, with secondary application to amplifiers. During World War II, Bode and BTL widely distributed the unpublished manuscript to other laboratories working on control systems.[70] Bode acknowledged a certain amount of "unnec-

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treatment in which pieces of Black's account are woven in with expository text of your own? . . . It might be possible to eliminate, for example, the references to Steinmetz and Hartley, which seem to me to be irrelevancies. In a less personalized account, it might be possible to present basic technological issues in a more satisfactory way. For example, as the paper now stands it seems to imply that Black deserves credit for the pioneer investigation of nonlinear effects in long systems. I doubt whether this is really accurate. . . . I was also a little disturbed by Harold's claim that he outfaced the U. S. Patent office on every one of 126 claims. I didn't know that the Patent Office gave ground that easily. In any case, credit should probably go to the long-suffering patent attorney who wrote all those letters." Bode to Dickieson, 17 September 1974, AT&T archives.

[66] Elsewhere he likened the feedback amplifier designer to "a man who is trying to sleep under a blanket too short for him. Every time he pulls it up around his chin his feet get cold." H. W. Bode, "Design Method for Feedback Amplifiers—Case 19878," 1 May 1936, AT&T archives.

[67] Bode, "Relations Between Attenuation and Phase in Feedback Amplifier Design."

[68] Ibid., 426–35.

[69] Bode, "Feedback: The History of an Idea," in Bellman (n. 2 above), 117.

[70] H. W. Bode, *Network Analysis and Feedback Amplifier Design* (New York, 1945), iii.

essary refinement" of the design methods in the book, but explains that they were required for telephone repeater amplifiers, with their unusually high standards for performance.[71] Even today, through Bode's plots, feedback techniques retain the traces of the network theory of the 1920s.

Speaking Machinery and the Transmission of Information

The work done by Black, Bode, and Nyquist brought negative feedback and the vacuum tube within the realm of signals, frequencies, and networks. The high-quality linear repeater amplifiers these men developed furthered the separation of the message inherent in the telephone signal from the energy required to transmit it down the line. Black's feedback amplifier aimed to regulate transmission and insulate the performance of the technical network from its physical and meteorological environment. Nyquist and Bode addressed the immediate problems of frequency response and dynamic stability. Because self-regulation could rapidly turn to oscillation, avoiding instability became a primary concern of feedback-amplifier design. Developing the feedback amplifier connected at every point to problems of the telephone network, including long-distance transmission, carrier modulation, and the role of fundamental research in the system overall.

Negative-feedback amplifiers evolved together with a conception of the network as a social device, and of machines as active speech producers—a vision actively supported by the new research organization. Technically, this vision incorporated both telegraphy and telephony, text and speech (and later images), into theories of processing signals, manipulating them in the frequency domain, and precisely matching them to transmission channels. Indeed, at the same time that Nyquist was theorizing negative feedback he was working out the relations between bandwidth and channel capacity, the interchangeability of telephone and telegraph signals, and the effect of noise on transmission rates. Nyquist also attacked the problem of chopping up a signal into discrete bits or "signal elements," transmitting them individually, and then using them to reconstruct the original signal. Today, Nyquist's "sampling theorem" still determines the rates at which our analog world is sampled and converted into digital form.[72] Similarly, BTL researcher Ralph

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[71] Ibid., iv.

[72] H. Nyquist, "Certain Factors Affecting Telegraph Speed," *Bell System Technical Journal* 3 (April 1924): 324–46. For telegraph sampling, the main paper was H. Nyquist, "Certain Topics in Telegraph Transmission Theory," *Transactions of the American Institute of Electrical Engineers* 47 (February 1928): 617–44. See also the discussion of this paper by Nyquist's son-in-law, John C. Lozier, "The Oldenberger Award Response: An Appreciation of Harry Nyquist," *Journal of Dynamic Systems, Measurement and Control* 98 (June 1976): 127–28. Nyquist's measure, that a wave must be sampled at twice its bandwidth to be transmitted without distortion, is frequently referred to as "the Nyquist rate." A modern

Hartley's work proposed quantitative measures for the transmission of signals independent of their nature or content. Nyquist and Hartley laid the groundwork for the theory of information that Claude Shannon would articulate in 1948.[73] And Homer Dudley, in an article titled "The Carrier Nature of Speech," explicitly compared human language to network traffic. At the Century of Progress Exposition in Chicago in 1933, the AT&T exhibit featured Dudley's speech synthesizer and promoted the company's new Teletypewriter services.[74] Other BTL researchers during these years developed automatic switches, talking movies, stereophonic sound, artificial organs for listening and speaking, and "invisible orchestras" for transmitting high-fidelity audio over the network.[75] Each furthered, in its own way, the abstraction of signals and the extension of human activity by the telephone's spreading network.

Developments in communications theory did not simply reflect technical systems and facilitate their convergence. They also supported AT&T's corporate goals. Frank Jewett, speaking to the National Academy of Sciences in 1935, rejected the distinctions between types of signals: "We are prone to think and, what is worse, to act in terms of telegraphy, telephony, radio broadcasting, telephotography, or television, as though they were

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CD player, for example, samples music at 44 kHz in order to reproduce it in the audible band of about 20 kHz. For Nyquist's work on noise, see "Thermal Agitation of Electric Charge in Conductors," 110–13.

[73] R. V. L. Hartley, "Transmission of Information," *Bell System Technical Journal* 7 (July 1928): 535–63. See brief discussions of Nyquist and Hartley by E. Colin Cherry, "A History of the Theory of Information," *Proceedings of the Institution of Electrical Engineers* 98 (September 1951): 386, and by J. R. Pierce, "The Early Days of Information Theory," *IEEE Transactions on Information Theory*, no. 1 (January 1973): 3. In his foundational paper on information theory, Shannon cited Nyquist's two papers on telegraph transmission, "Certain Factors Affecting Telegraph Speed" and "Certain Topics in Telegraph Transmission Theory," and Hartley's "Transmission of Information" in the first paragraph. Claude Shannon, "A Mathematical Theory of Communication," parts 1 and 2, *Bell System Technical Journal* 27 (July/October, 1948), 379–423, 623–56, reprinted in *Claude Elwood Shannon: Collected Papers*, ed. N. J. A. Sloane and Aaron D. Wyner (New York, 1993), 5–83.

[74] Homer Dudley, "The Carrier Nature of Speech," *Bell System Technical Journal* 19 (October 1940): 495–515. "The Bell System Exhibit at the Century of Progress Exposition" *Bell Laboratories Record* 11 (July 1933).

[75] Kenneth Lipartito, "When Women Were Switches: Technology, Work, and Gender in the Telephone Industry, 1890–1920," *American Historical Review* 99 (October 1994): 1074–111. Sheldon Hochheiser, "What Makes the Picture Talk: AT&T and the Development of Sound Motion Picture Technology," *IEEE Transactions on Education* 35, no. 4 (November 1992): 278–85. Harvey Fletcher, "The Nature of Speech and Its Interpretation," *Bell System Technical Journal* 1 (July 1922): 129; "Physical Measurements of Audition and Their Bearing on the Theory of Hearing," *Bell System Technical Journal* 2 (October 1923): 145; "Useful Numerical Constants of Speech and Hearing," Bell System Technical Journal 4 (July 1925): 375–86. Robert E. McGinn, "Stokowski and the Bell Telephone Laboratories: Collaboration in the Development of High-Fidelity Sound Reproduction," *Technology and Culture* 24 (1983): 43.

things apart." Jewett argued instead that these technologies merely represented different embodiments of a common idea of communication. "[T]hey are merely variant parts of a common applied science. One and all, they depend for the functioning and utility on the transmission to a distance of some form of electrical energy whose proper manipulation makes possible substantially instantaneous transfer of intelligence."[76] Government regulation persisted in making distinctions between media (radio, telephony, and so on), each controlled by their own vested interests. When policy followed science and treated all signals as equivalent, Jewett argued, then AT&T, with its natural monopoly, would emerge as the unified communications company: a builder of transmission, a carrier of long-distance signals, and a switcher of information.

Jewett's vision echoed Theodore Vail's "one policy, one system" motto, updated by the advances in technology, theory, and the organization of research at AT&T in the 1920s and 1930s. Feedback theory at Bell Labs contributed to the rapidly converging ideas about signals and communications that Jewett articulated. It was in this environment that Harold Black had his vision of feedback on the Lackawanna ferry in 1927.

Still, despite Jewett's call to unify communications, Black, Nyquist, and Bode kept their ideas within the existing network. They did not see their contributions to feedback theory as significant to the world of governors, regulators, servomechanisms, or automatic controls. Contrary to Black's recollection, the realization that feedback described common phenomena in a variety of settings did not crystallize until World War II, when new institutions brought engineers from diverse backgrounds together to construct military control systems. Only then were the techniques developed at BTL to deal with feedback, frequencies, and noise applied to mechanical and hydraulic systems, and to the human operators themselves. Only then did feedback become prominent as a general principle in engineering, and only afterward, with the work of Norbert Wiener, Claude Shannon, and numerous others, did Black's, Bode's, and Nyquist's ideas move beyond amplifiers and into a broad range of disciplines. Feedback is indeed fundamental to our technological world, but Harold Black's epiphany, more than a foundational moment, was one of a series of technical insights that allowed engineers to separate human communications from their electrical substrates, to send them through geographically extensive networks, and to represent the world in a common language of signals.

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[76] Frank B. Jewett, "Electrical Communication, Past, Present, and Future," speech to the National Academy of Sciences, April 1935, reprinted in *Bell Telephone Quarterly* 14 (July 1935): 167–99.