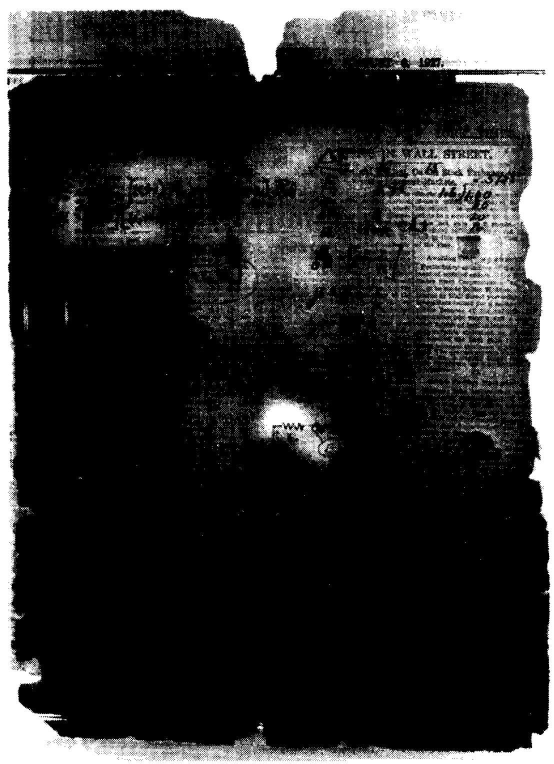
Harold Black and the Negative-Feedback Amplifier

Ronald Kline

On August 2, 1927, Harold Black, a young Bell Labs engineer just six years out of college, invented the negative feedback amplifier in a "flash of insight" while riding the Lackawanna Ferry across the Hudson River on his way to work. (Bell Labs was then located on West Street in Manhattan.) Black recalled, "I felt an urge to write but had nothing to write on so picked up my morning paper. By sheer coincidence one page was blank. Here was a perfect set-up, lots of room and fully dated. With this to implement my job, I started the first written record pertaining to the stabilized negative feedback amplifier. Years of study and many failures preceded this sudden conception of stabilized feedback. Despite immediate recognition of its importance, years of additional work were required before it found substantial commercial use" [1, p. 723].



One of the newspaper pages used by Black to jot down his early ideas on feedback. (Photo: AT&T Archives)

Negative feedback became widespread [2]. It allowed the Bell system to reduce overcrowding of lines and extend its long-distance network by means of carrier telephony. It enabled the design of accurate fire-control systems in World War II, and it formed the basis of early operational amplifiers, as well as precise, variable-frequency audio oscillators. With the transition from vacuum tubes to microelectronics after World War II, negative feedback retained its status as an integral part of communications and control systems because it was associated with network theory from the beginning. Like Maxwell's circuit equations, which were developed in the 1860s to understand the induction coil, negative feedback was not tied to the technology of its origins (vacuum tubes) and became a fundamental principle of electrical engineering with innumerable applications independent of the original hardware used for its invention.

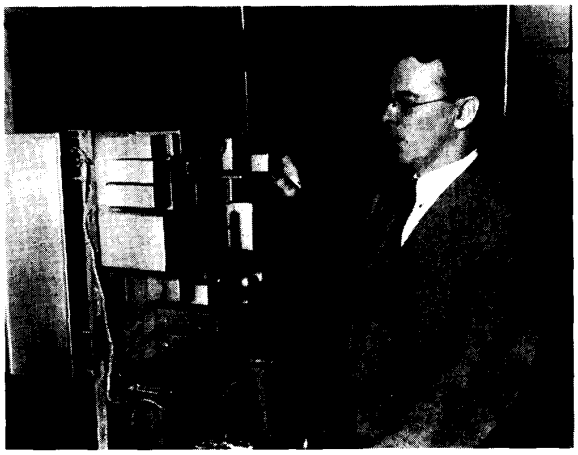
Invention

The journey to the Lackawanna Ferry began in 1921, when Harold Black (1898-1983) graduated from Worcester Polytechnic Institute with a Bachelor's degree in electrical engineering and took a job with the Engineering Department at Western Electric. (The research branch of this department formed the nucleus of Bell Labs when it was established in 1925.) A pressing problem in the Bell system at the time was that the distortion and instability of vacuum-tube amplifiers were compounded when they were connected in tandem over a long-distance system based on carrier telephony. (Carrier telephony became feasible in 1917 with the invention of a practical wave filter by George Campbell, an AT&T researcher who had invented the loading coil independent of Michael Pupin around 1900.)

The gain of the amplifiers varied with plate voltage, temperature, aging of the tubes, etc., while the nonlinearity of the

The author is with the College of Engineering and the Science and Technology Studies Department, Cornell University, Ithaca, NY 14850. *This work was supported by the National Science Foundation, Engineering Education Coalition, Synthesis project, headquartered at Cornell University Summer 1991.*

tubes created intermodulation distortion in the multichannel carrier system. In 1921, engineers were facing these difficulties on the transcontinental telephone line, built in 1915 but recently "upgraded" to a three-channel system with twelve amplifiers. Bell built a second transcontinental line in 1923 with four channels and twenty amplifiers, and was planning more complex systems for the future [3].



Harold S. Black in 1941 with some of the amplifying equipment that used his idea for reducing distortion by reversing some of the amplifier's output and feeding it back into the input. (Photo: AT&T Archives)

Black became intrigued with the problem that year and asked his supervisor for permission to work on improved amplifiers for a system numbering thousands of channels. The supervisor was apparently "bemused by the scale of his thinking" [4, p. 63] and agreed to let him pursue the topic, provided it did not interfere with his other work. Black approached the problem by trying to make vacuum tubes operate in a more linear fashion, i.e., he wanted to make the active elements of the amplifier produce less distortion. Mervin Kelly, well-known later as the head of Bell Labs when his researchers invented the transistor in 1947, was then in charge of electron tube research and cooperated with Black on the endeavor, but to no avail [5].

Black then had an important insight that helped him "reframe" the problem. He recalled that in 1923, "I attended a lecture by C. P. Steinmetz [chief engineer at General Electric] at an AIEE meeting [the American Institute of Electrical Engineers, a forerunner of the IEEE] and was impressed by the Steinmetz way of getting down to the fundamentals of a problem. As a result I restated my assignment as being that of removing distortion products from the amplifier output. I immediately observed that by reducing the output to the same amplitude as the input and subtracting one from the other, the distortion products only would remain which could then be amplified in a separate amplifier and used to cancel out the distortion products in the original amplifier output ... Thus, the Feedforward Amplifier came into being" [4, pp. 64-65].

Although not based on negative feedback, this amplifier was an essential step to its invention because Black had reformulated the problem. He was no longer trying to prevent vacuum tubes from causing distortion. He accepted that distortion and sought a way to reduce it at the output of the amplifier. This was a critical step and put him on the track to the eventual solution.

Although resurrected in the 1970s for single-sideband microwave radio, the feedforward amplifier did not work well for carrier telephony in the 1920s. Black applied for a patent on the invention in February 1925, which was issued in October 1928 [6], and then, as a member of a development group at Bell Labs, tried to make it work in a systems environment. He built an experimental amplifier to reduce the invention to practice, but precise balances and subtractions of signals were hard to achieve and maintain in practice.

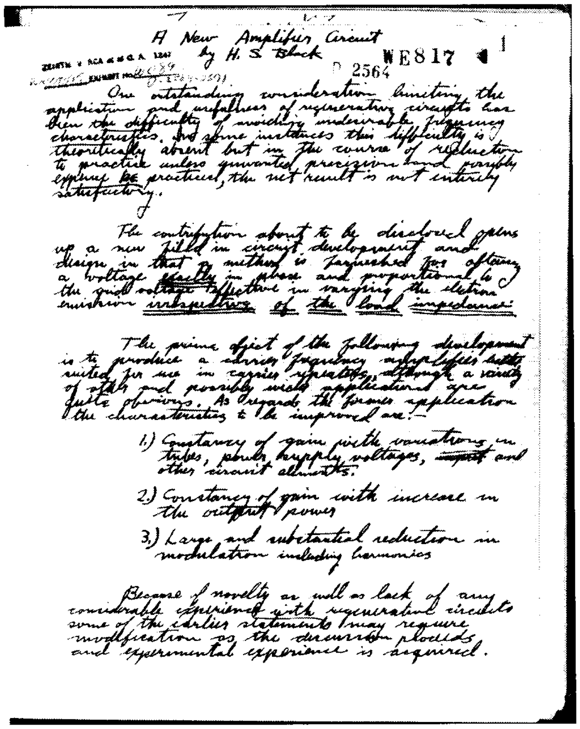
This was the state of Black's work on telephone amplifiers in 1927, the year of the famous flash of insight on the Lackawanna Ferry. What occurred between the feedforward experiments and that fateful morning on the Ferry is not clear. Negative feedback was a concept diametrically opposed to feedforward and was not an obvious direction to explore. Black probably knew about the two main types of feedback at the time: 1) the comparison of output and input signals to generate an error signal to control the output, which had been widely used in mechanical and electrical control systems [7]; and 2) positive feedback, which had been used for oscillation and increased amplification (regeneration) in radio equipment since about 1913 [8]. But Black took a much different approach. He used negative feedback to reduce the amplification of a very high-gain device. Correctly designed, negative feedback reduced distortion and noise, while stabilizing gain by making it dependent on the passive feedback network, instead of the troublesome active elements (vacuum tubes). Two other AT&T researchers, H.T. Friis and A.G. Jensen, had investigated the feedback caused by the plate-to-grid capacitance in a vacuum tube and its influence on amplification in 1924. They noted this feedback could increase or decrease the amplification (i.e., be positive or negative). But they regarded plate-to-grid feedback as an unwanted phenomenon in amplifiers, to be neutralized by adding a capacitor, and did not see the benefits of negative feedback [9].

Black probably knew about their work because it was published in the *Bell System Technical Journal*, but it is unclear if it influenced his research. Black recalled that he was working on the feedforward and other related topics when he had the insight about negative feedback. Mervin Kelly, however, said, "Finally, a mathematical analysis convinced him that by merely inserting a part of the output power into the input in negative phase, he could obtain any desired reduction in distortion products at the expense of a sacrifice in amplification. His *final mathematical analysis* was conceived while he was crossing the Hudson River on the Lackawanna Ferryboat en route from home to the laboratories" [5, p. 722, my emphasis].

Black had the page of *The New York Times* witnessed by a co-worker the morning of his insight, then set out to build his amplifier and prepare a patent application. He submitted an extremely long application (52 pages, 126 claims) in 1928, but the patent office objected to many of the claims, apparently because his concept of negative feedback flew in the face of accepted theory. The examiners finally awarded the patent nine years later, in December 1937 [10], after Black and others at AT&T developed both a practical amplifier and a theory of negative feedback.

Development

As Black recalled, the road from the Lackawanna Ferry to a practical amplifier was long and rocky. He had a difficult time with the amplifier "singing" (breaking into oscillations) and devised a design rule to guard against this instability. In May 1928, Harry Nyquist (1889-1976) and other communication engineers at AT&T conferred with Black about using his amplifier for a new cable carrier system. Nyquist, who received his Ph.D. in physics from Yale in 1917, thought Black's design rule was too stringent and did an analysis of negative feedback. This work led to what later came to be known as the "Nyquist criterion" for determining when an amplifier with negative feedback was stable. He published the paper containing the criterion in 1932 during the patent office deliberations on Black's patent and joined Bell Labs in 1934 [11]. Black recalled, "Although this criterion is simple in expression and application, Nyquist's derivation of it required a mathematical-physical intuition given to few men" [1, p. 723]. Black's classic paper on the negative feedback amplifier, published in 1934, referred to Nyquist's paper and his stability criterion [12].


A New Amplifier Circuit
by H. S. Black
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One outstanding consideration limiting the application and usefulness of regenerative circuits has been the difficulty of avoiding undesirable frequency characteristics. In some instances this difficulty is theoretically absent but in the course of reduction to practice unless unwanted precision and possibly expense be practiced, the net result is not entirely satisfactory.

The contribution about to be disclosed opens up a new field in circuit development and design in that a method is furnished for obtaining a voltage exactly in phase and proportional to the grid voltage effective in varying the electron emission irrespective of the load impedance.

The prime object of the following development is to produce a carrier frequency amplifier [illegible] suited for use in carrier repeaters, although a variety of other and possibly wider applications are quite obvious. As regards the former application the characteristics to be improved are:—

1.) Constancy of gain with variations in tubes, plate supply voltages, [illegible] and other circuit elements.

2.) Constancy of gain with increase in the output power

3.) Large and substantial reduction in modulation including harmonics

Because of novelty as well as lack of any considerable experience with regenerative circuits some of the earlier statements may require modification as the discussion proceeds and experimental experience is acquired.

A page from Harold Black's notebook, probably late 1920. (Photo: AT&T Archives)

In that same year, during the development of a coaxial-cable carrier system with a passband of 1 MHz and the possibility of several hundred amplifiers, another Bell Labs theorist, Hendrik Bode (1905-1982), led a group of mathematicians in the development of design techniques that took full advantage of Black's invention [13]. Bode, an applied mathematician who received an M.A. from Ohio State in 1926 and a Ph.D. in physics from Columbia University in 1935 [14], published his paper, "Relations Between Attenuation and Phase in Feedback Amplifier Design," in 1940 [15]. The paper, and a resulting book in 1945 (which included what engineers now call "Bode plots"), used the powerful tools of network theory to show how to design feedback amplifiers with the desired gain and frequency response in a precise manner [16]. Thus, although Black is usually recognized as the inventor of the negative feedback amplifier, its development and the recognition of its possibilities in communications, measurements, and control systems were the result of a group effort between engineers and theorists with advanced training in mathematics and physics — a common aspect of the history of electronics in this period.

Hewlett-Packard and the Negative Feedback Amplifier

The application of the negative feedback principle was taken up fairly rapidly at Stanford University by electrical engineering professor Frederick Terman and his students. In 1939, Terman, William Hewlett, Robert Buss, and Francis Cahill wrote a paper that described many uses for negative feedback: in a laboratory audio-frequency amplifier, an audio-frequency voltmeter, a tuned-radio receiver, high-Q circuits, and laboratory oscillators. Negative feedback resulted in low distortion, stable gain, and a small phase angle, while protecting the circuits from the harmful effects of vacuum-tube aging, variable supply voltages, and so forth. These characteristics were of high value in precision voltmeters, oscilloscopes, and oscillators. Terman, who often is called the founder of what came to be known as "Silicon Valley" because of his promotion of commercial ties between Stanford and local electronics firms [17], recalled in the 1970s that the "resistance-capacitance tuned variable frequency audio oscillator described in this paper was William Hewlett's contribution to the paper, and was furthermore the foundation on which the Hewlett-Packard Company was built" [18].

The history of H-P's founding has elements of the stereotypical story of independent inventors working alone in a garage. David Packard and Hewlett did start their company in Packard's garage (Hewlett lived in a cottage on the grounds). But the influence of Stanford and Terman was considerable. Hewlett and Packard returned to the area after graduating from Stanford in 1934. Packard took a leave of absence from GE to accept a fellowship in 1938, while Hewlett returned to work under Terman after finishing a Master's degree at M.I.T. in 1936. Terman encouraged the pair to form a company to market Hewlett's variable-frequency oscillator, lent them $538, helped them get a bank loan of $1000, and helped them work out a deal with IT&T who bought their international patent rights in exchange for underwriting their U.S. patent application. An early customer for the audio-frequency oscillators was Disney Studios, who ordered eight for the film "Fantasia." By 1940, the fledgling company had nine employees and had moved out of the garage to develop a full line of products — based initially on the negative-feedback amplifier [19].

Common Themes

The story of this amplifier illustrates many themes in the history of technology. Although the invention can be traced to a "flash of insight" by a single person, the inventor was well trained in mathematics, engineering, and science, and had been working with others in this area. The development of the amplifier was truly a team effort at Bell Labs; theorists with excellent mathematical skills developed a theory that helped engineers understand the original invention and develop it further. The application of the invention by Hewlett and Packard not only started a new business, but reinforced the connections between the university and the electronics industry that became a characteristic of what people later called the Silicon Valley style of invention. Thus, the history of the negative-feedback amplifier is an excellent example of the complex interplay between theory, experiment, and practice in the institutional settings of established industrial research labs, booming businesses, and expanding universities that became common in the U.S. electronics industry after World War II [20].

Acknowledgment

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CORRECTION

The footnote to the article "Sliding Mode and Classical Controllers in Magnetic Levitation Systems," by Dan Cho, Yoshifumi Kato, and Darin Spilman (*IEEE Control Systems Magazine*, Feb. 1993, pp. 42) incorrectly identified part of Y. Kato's company affliation. Kato was on leave from "Nippondenso Co., Ltd." (not "NipponDenso Co.," as stated in the footnote).