Innovation

Inventing the negative feedback amplifier

Six years of persistent search helped the author conceive the idea "in a flash" aboard the old Lackawanna Ferry

Recently, while watching television at my home in New Jersey, I was pleasantly surprised to see a commercial for a computer-controlled sewing machine. It was the latest of many applications of the negative feedback amplifier that I could never have envisioned when I invented the amplifier more than 50 years ago as a 29-year-old systems engineer at the Western Electric Company's old West Street laboratories in New York City. Although I was certain the amplifier would see broad use inside as well as outside of the Bell System, I did not foresee the tremendous range of applications that would open up for it in almost every type of communication and control system, from radio to automatic pilots, from computers to artificial limbs. The enormous impact of what I had conceived while traveling to work one sunny August morning in 1927 has proved extremely gratifying. I am proud that the amplifier is used today in more than 85 countries and that it has played such an important role in the technological revolution of the past half-century.

The path to the invention, which I shall retrace in this article, began July 5, 1921, when I joined the forerunner of Bell Laboratories at the then handsome salary of $32 a week. I had just been graduated from Worcester Polytechnic Institute with a B.S.E.E. degree signifying completion of a course of study that included surveying, hydraulics engineering, pattern making, drop forge, and machine shop, in addition to physics, chemistry, and mathematics. After a 12-week training program, I was accepted into the Systems Engineering Department, which appealed to me more than such areas as "apparatus" because it seemed less limited and involved contacts with the other departments. The department was headed by Amos Dixon, an eighth-grade graduate who took correspondence courses and worked his way up to a position in the organization that today would correspond to a vice presidency.

The telephone industry was an exciting place for a young engineer in 1921. Only a few years had passed since Lee de Forest's 1906 audion tube had been made into the practical high-vacuum device needed for long-distance telephone lines. In 1915, the 68-year-old Alexander Graham Bell had placed the first official transcontinental call to Thomas Watson, his famous assistant 40 years earlier, and in 1914, a young Edwin Howard Armstrong had sat through a bitterly cold January night with David Sarnoff in an American Marconi wireless shack testing Armstrong's new "regenerative" receiver, which utilized positive feedback.

Wiring the nation

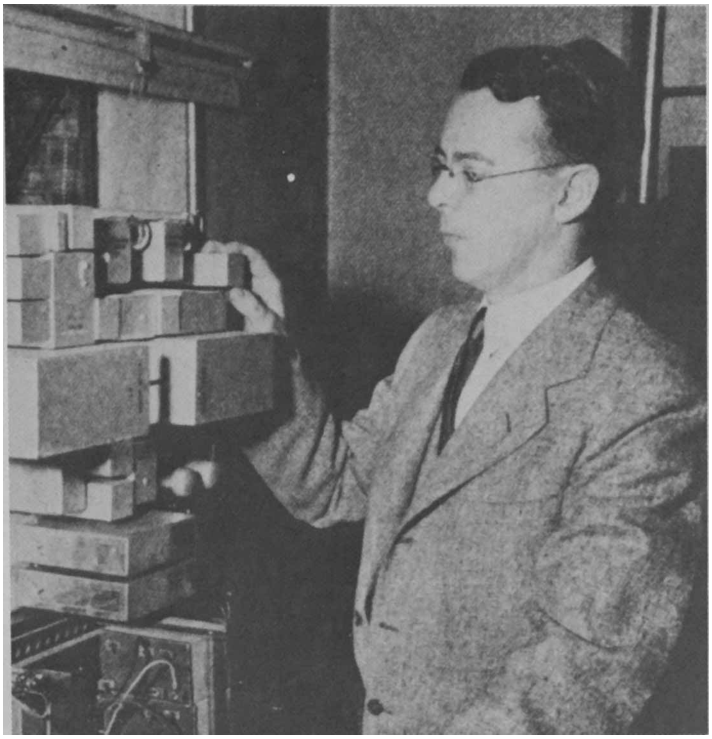
In 1921, the major task confronting the West Street laboratory was to improve the Bell System's new open-wire telephone systems. In these systems, voice-frequency currents were used to modulate a high-frequency current, which thus served as a "carrier" for the message. The newest, a three-channel system called the Type C, was having problems with distortion and crosstalk that September, when I started in the systems department—but I had my own problems. The other June graduates who had started with me, but at a salary of $27 a week, were raised to $30. I did not receive a raise and promptly decided to resign the next day and perhaps work my way through business school. Fortunately, I thought better of the idea by morning because I could have never been a businessman and this would have been the biggest mistake of my life. Instead, I made up my mind to learn everything I could about Western Electric and the telephone business.

In those days, everything of importance an employee wrote was kept as a "memorandum-for-file," and I began coming in on Sundays to read the file, starting with 1898, the year I was born. By the time I had reached 1921, I was hitting pay dirt—a look at what was happening on all 12 floors at 463 West Street. I learned the names of all the engineers and their supervisors, exactly who reported to whom, what kinds of technical problems faced them, and so on.

In this way, and as a result of the small initial assignments I was given in connection with the Type C system, I discovered that the system's push-pull repeater amplifiers were a major source of trouble. No one knew how to make amplifiers linear or stable enough in those days, and consequently they were subject to an intolerable amount of distortion. The problem lay with the unwanted frequencies generated by the vacuum tubes, particularly the second-order harmonics and other products that

Harold S. Black Consultant

While crossing the Hudson on August 6, 1927, the author used a page of *The New York Times* to sketch this scheme for matching the output impedance of his new amplifier to the line or cable. At right is the Lackawanna Ferry on which he was commuting to work that day, and five days earlier when he conceived the original idea for the amplifier (see Fig. 2).



Black holds one of the condensers from a negative feedback amplifier being tested at Morristown, N.J., field trials in 1930. An intermittent fault in the condenser had threatened to terminate the test and, says Black, his job as well.

predominated. Theoretically, this type of amplifier should have suppressed all second-order harmonics and products, but in actuality they were only reduced to 10–18 percent.

Envisioning a new telephone system

I began thinking about how the performance of repeater amplifiers might be improved, and—more important—how they might be designed so that one could have carrier systems with many amplifiers in tandem, each handling many channels. Existing systems like the Type C were not expected to go farther than 1000 miles, and the largest repeater anyone had built to date could only accommodate four channels. I could not imagine that such systems would be adequate in a country 4000 miles across, where one would need a whole network of spares as well as operating amplifiers. With the invention of the so-called hard vacuum tube by Harold de Forest Arnold (no relation to Lee de Forest), we were able to get one voice channel on a coast-to-coast open-wire system. I foresaw a need for many, many channels, and I knew it wouldn't be practical on a link that consisted of open wire.

The first thing I did about the problem took place on Thanksgiving Day, 1921. At home (a rented room in Roselle Park, N.J.), I plotted one curve showing how linearity would vary with the number of channels and another curve showing how it would be affected by adding more push–pull amplifiers in the string. Here, I made a significant error. I assumed that the unwanted third-

Telephone terminal equipment looked like this when Harold Black went to work at the Western Electric laboratory on West Street in September 1921.

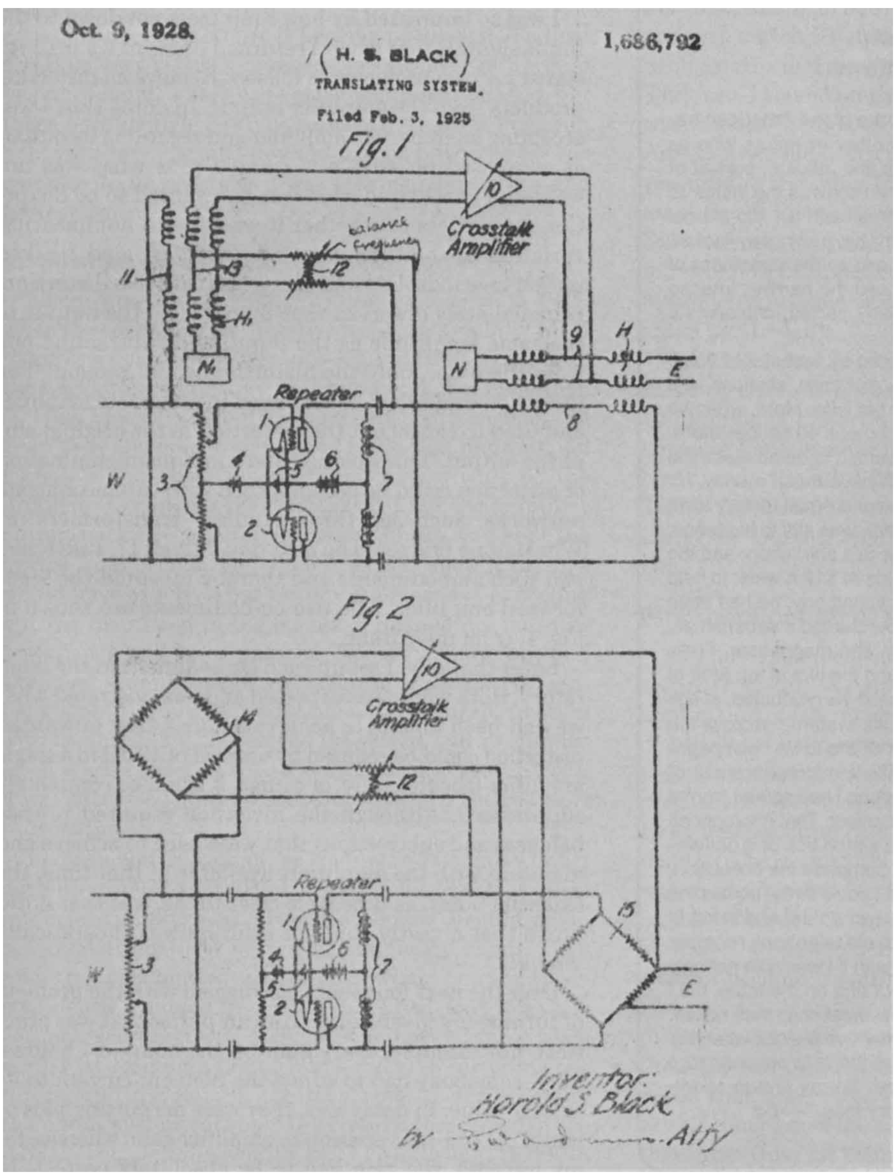
order harmonics and other products would behave precisely like the second-order harmonics; namely, be reduced to 10–18 percent as well. This meant that in a string of amplifiers the cumulative distortion would increase by an amount roughly equivalent to the square root of the number of amplifiers.

The next day at the laboratory I dropped in on Ralph Hartley, who was in the nearby Research Department. A Rhodes scholar whom I liked and respected very much (he would later invent magnetic parametric amplifiers and logarithmic information measure), my problem was right in his field, for he had worked on third-harmonic modulators. I described my results to Hartley and on the following day he sent me a note pointing out my error—namely, that, regardless of the type of amplifier, the third harmonics and all third-order modulation products contributed by a string of x amplifiers are virtually x times that contributed by a single amplifier. This meant that if I had a string of 1000 amplifiers the cumulative voltage distortion would amount to 60 dB. It was bad enough to have a lot of channels going through one amplifier, but to pile on distortion of this magnitude made it clear that I faced many serious problems in building strings of multichannel amplifiers.

After being corrected by Hartley, I prepared a chart plotting the severe distortion and linearity requirements imposed on a single multichannel amplifier as a function of the number of channels N, where N varied from one to 3000. This chart also showed that for a string of x amplifiers the distortion contributed by each amplifier must be divided by x. I immediately showed this chart to J. S. Jammer, then my supervisor, who had only one comment: "A beautiful piece of work, but why bother about so many channels?" Jammer apparently did not see why I should concern myself with 3000 channels when nobody else seemed to be bothering about more than three.

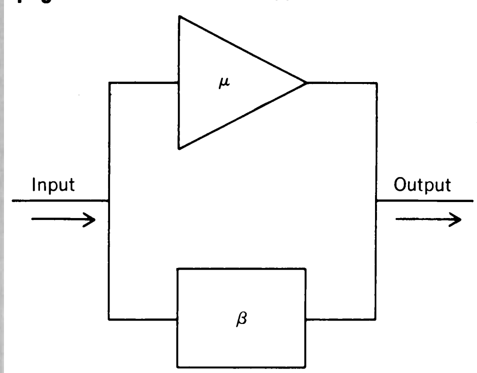
Search for a solution

I was determined to succeed, and on December 27, 1921, asked to be assigned the task of linearizing, stabilizing, and otherwise improving amplifiers so that a large number of multichannel amplifiers could be connected in tandem to carry conversations over distances of several thousand miles. Jammer's answer was, in effect, "Yes, provided it does not interfere with your other work," which at that time involved redesigning several kinds of push–pull amplifiers.



[1] Black's feedforward amplifier was conceived the day after he attended an inspiring lecture by Steinmetz.

[2] The concept of the negative feedback amplifier came to Black "in a flash" on August 2, 1927, while he was traveling to work on the ferry. He sketched these equations and block diagram on a page of *The New York Times*.



$$\frac{\text{Output}}{\text{Input}} = A_F = \frac{\mu}{1-\mu\beta}$$

$$= \frac{1}{-\beta}\left[1 - \frac{1}{1-\mu\beta}\right]$$

During the next two years, I spent many weekends and evenings reading all I could about the unwanted generation of products of modulation due to nonlinear response and the design theory of modulation and related nonlinear circuits. In addition, I read a large number of company memoranda-for-file that treated these and related topics in greater detail. These studies showed that the job would require an amplifier vastly superior to any then existing. As W. E. Doherty of Bell Labs pointed out in a retrospective article several years ago: "The repeater problem looked almost insoluble because no one knew how to make the amplifiers linear enough or stable enough. If only a factor of ten had been needed, it might have been possible to do it, with hard work, in some straightforward way; but an improvement of hundreds or thousands was needed, not just ten."

During this period, many other Western Electric research people were also aware of the need to reduce amplifier distortion so that a large number could be operated in tandem. Their only approach, and indeed mine, was to try to linearize the tube characteristic. For several months, I worked closely with Mervin Kelly, a great friend who would later be president of Bell Labs. Among other achievements, he received credit for initiating the program that ultimately led to the invention of the transistor by John Bardeen, Walter Brattain, and William Shockley. Kelly was then in charge of electron tube research and his "tube shop" on nearby Hudson Street had designed every vacuum tube that Western Electric manufactured. Despite his formidable talents, however, we were unsuccessful. There was just no way to meet our ambitious goal of a tube with less than 50-dB distortion.

An encounter with Steinmetz

This might have been the end of it except that, on March 16, 1923, I was fortunate enough to attend a lecture by the famous scientist and engineer, Charles Proteus Steinmetz. The meeting was held at the AIEE auditorium in New York City, and I remember arriving early in order to get a seat in the front row. Soon every seat was taken. Dr. Steinmetz was 20 minutes late, but he was given a standing ovation as he walked down the center aisle dressed in blue overalls and a blue shirt with short sleeves and smoking the largest cigar I had ever seen. It was an inspiring lecture. I no longer remember the subject, but I do remember the clarity and logic of his presentation and how quickly and directly he reached the final conclusion of his talk.

I was so impressed by how Steinmetz got down to the fundamentals that when I returned home at 2 a.m., I restated my own problems as follows: Remove all distortion products from the amplifier output. In doing this, I was accepting an imperfect amplifier and regarding its output as composed of what was wanted plus what was not wanted. I considered what was not wanted to be distortion (regardless of whether it was due to nonlinearity, variation in the tube gain, or whatever), and I asked myself how to isolate and then eliminate this distortion. I immediately observed that by reducing the output to the same amplitude as the input, and subtracting one from the other, only the distortion would remain. The distortion could then be amplified in a separate amplifier and used to cancel out the distortion in the original amplifier output. This isolation and subsequent elimination of distortion could be accomplished with two biconjugate networks such as three-winding transformers or Wheatstone bridges. The next day, March 17, I sketched two such embodiments and thereby invented the feedforward amplifier. The two embodiments are shown in Fig. 1, from my patent.

Later that day, I set up each embodiment in the laboratory. Both worked as expected and demonstrated what we had been unable to achieve before—that unwanted distortion could be reduced by upward of 40 dB in a single amplifier (theoretically, of course, it could be completely suppressed). Although the invention required precise balances and subtractions that were hard to achieve and maintain with the amplifiers available at that time, the essential point, as it became clear to me, was that it did prove that a vastly superior solution was theoretically possible.

Over the next four years, I struggled with the problem of turning my invention into an amplifier that was practical. For example, every hour on the hour—24 hours a day—somebody had to adjust the filament current to its correct value. In doing this, they were permitting plus or minus ½- to 1-dB variation in amplifier gain, whereas, for my purpose, the gain had to be absolutely perfect. In

Harold Black and his first telecommunications system

Harold Black is very much part of the grand American tradition of Edison, Armstrong, and other inventors who as boys tinkered in Victorian cellars and attics in pursuit of fame and fortune. Today, at 79, he receives the visitor to his comfortable New Jersey home with an old-school graciousness that is enhanced by his natty grey jacket, white shirt, and navy blue slacks, and by the steadiness of his gaze behind rimless glasses and the narrow, intense face that welcomes beneath neatly parted, china-white hair.

In his spacious study, surrounded by technical books, journals, papers, correspondence, diplomas, citations, and a large transparent oil painted by his wife, Meta, when he still smoked a pipe and weighed perhaps 40 pounds more, Dr. Black recalls that he always wanted to be an electrical engineer. Why? "Because I didn't have much money."

He was born in Leominister, Mass., a small factory town near Worcester. When Harold Black was still in his teens, his father lost his job as a shipper in a shirt shop, and the youngster went to work ironing shirts at $12 a week to help support their family of four. As a young boy, he had been intrigued by electricity, and had purchased a set of small, inexpensive books on electricity and magnetism. From early experiments with buzzers and the like in the attic of the two-story house the family rented, he graduated, at age 16, to his first "telecommunications system." Across the street, he recalls, lived the editor of the town newspaper and his five daughters. "So I made a microphone out of pieces of wood, two pieces of carbon I had sawed from a battery, a tin can, and a spring for contact. That microphone was so sensitive you could hear a watch tick or a conversation anywhere in the house. To complete the collection, I took a piece of very fine wire that I could throw across the street to their house, catch onto two poles, and bring in downstairs. Up in the attic I had an old telephone receiver that somebody had discarded and with it I was able not only to hear a watch tick, because I put one on the table, but I was able to hear every word of conversation in their house. And that worked fine until a little after five o'clock when the father came home. He destroyed the microphone, tore down the wires, and said no more. So my first telecommunications system didn't last very long."—*Ed.*

Mervin Kelly upon the presentation of the 1957 Lamme Medal to Harold Black

Although many of Harold's inventions have made great impact, that of the negative feedback amplifier is indeed the most outstanding. It easily ranks coordinate with De Forest's invention of the audion as one of the two inventions of broadest scope and significance in electronics and communications of the past 50 years. . . . It is no exaggeration to say that without Black's invention, the present long-distance telephone and television networks which cover our entire country and the transoceanic telephone cables would not exist. The application of Black's principle of negative feedback has not been limited to telecommunications. Many of the industrial and military amplifiers would not be possible except for its use. Many new weapons, such as radio detection of bombing and radar control of missiles, are dependent on negative feedback for their success. The development of servomechanisms theory and its application are extensions of Black's principle of feedback and are generally recognized as such. Thus, the entire explosive extension of the area of control, both electrical and mechanical, grew out of an understanding of the feedback principle. This principle also sheds light in psychology and physiology on the nature of the mechanisms that control the operation of animals, including humans, that is, on how the brain and senses operate.

addition, every six hours it became necessary to adjust the B battery voltage, because the amplifier gain would be out of hand. There were other complications too, but these were enough! Nothing came of my efforts, however, because every circuit I devised turned out to be far too complex to be practical. I was seeking simplicity—and perfection.

Inspiration on the Lackawanna Ferry

Then came the morning of Tuesday, August 2, 1927, when the concept of the negative feedback amplifier came to me in a flash while I was crossing the Hudson River on the Lackawanna Ferry, on my way to work. For more than 50 years I have pondered how and why the idea came, and I can't say any more today than I could that morning. All I know is that after several years of hard work on the problem, 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. I opened my morning newspaper and on a page of *The New York Times* I sketched a simple canonical diagram of a negative feedback amplifier plus the equations for the amplification with feedback (Fig. 2). I signed the sketch, and 20 minutes later, when I reached the laboratory at 463 West Street, it was witnessed, understood, and signed by the last Earl C. Blessing.

I envisioned this circuit as leading to extremely linear amplifiers (40 to 50 dB of negative feedback), but an important question is: How did I know I could avoid self-oscillations over very wide frequency bands when many people doubted such circuits would be stable? My confidence stemmed from work that I had done two years earlier on certain novel oscillator circuits and three years earlier in designing the terminal circuits, including the filters, and developing the mathematics for a carrier telephone system for short toll circuits (described in the *AIEE Transactions*, vol. 48, pp. 117–140, Jan. 1929). In the course of this work, I had computed and measured transfer factors around feedback loops and discovered that for self-oscillations to occur the loop transfer factor must be real, positive, and greater than unity at some frequency. Consequently, I knew that in order to avoid self-oscillation in a feedback amplifier it would be sufficient that at no frequency from zero to infinity should $\mu\beta$ be real, positive, and greater than unity. Accordingly, I immediately proceeded with the careful design and development of a working model of a three-stage broadband negative feedback repeater amplifier while C. W. Weiss started gathering the parts. Within a few weeks, we had a model working, although much additional work had to be done to establish the final circuit configuration and all of the circuit constants.

A fundamental requirement of a repeater amplifier is that its input and output impedances must accurately match those of the line or cable to which the amplifier connects. This had generally been considered difficult to accomplish without losing considerable input signal and output power. However, during another ride on the same ferry, I sketched the details of how to accomplish this impedance match for the output impedance of a negative feedback amplifier, once again using a page of *The New York Times* (see lead illustration). This was Saturday, August 6, 1927. The circuit employed a novel biconjugate network, which, in addition to providing a precision impedance match (thanks to negative feedback), simultaneously afforded a convenient way of connecting μ to β. This, too, I signed on the ferryboat, and later the sketch was witnessed, understood, and signed by Earl Blessing. An exactly similar circuit arrangement is required and was used in the input of the negative feedback repeater amplifier. While this technique does not adversely affect the transmission from μ to β, or vice versa, the desired input or output impedance of the feedback amplifier can approach any value of Z whatsoever, and any error is divided by $(1 - \mu\beta)$.

On December 29, 1927, using typical input signals covering a frequency band extending from 4 to 45 kHz, a reduction of distortion of 100 000 to 1 (50 dB) was realized in a single amplifier—which was more than sufficient to do the job I had undertaken six years earlier. These final results were immediately transmitted to Harry A. Burgess, patent attorney at Bell Laboratories.

First application of negative feedback

January 1928 marked the start of the development of a carrier system for transcontinental cables—the first application of the invention. Utilizing a frequency band of 4 to 40 kHz, the system was supposed to transmit nine voice channels on a single no. 16 AWG (1.3-mm-diameter) nonloaded paper-insulated pair in an underground cable. Each underground cable was to contain 68 such paper-insulated pairs, and the spacing between the repeaters was to be 25 miles.

I had confided the results of my experiments to Frank B. Jewett, who was then president of Bell Labs and with whom I became friendly soon after starting at Western Electric. Dr. Jewett encouraged me to develop my amplifier for the new system, but Harold de Forest Arnold, then director of research at Bell Labs, objected. He insisted that a negative feedback amplifier would never work. I don't know the reason behind his doubts; possibly they arose from his training as a physicist. He instructed me to build, instead, a very powerful two-stage Colpitts push–pull amplifier that would operate at a level low enough to meet the overall requirements of 160 such amplifiers in tandem. I complied with his instructions, but at the same time pushed ahead with laboratory trials of six models of the negative feedback amplifier. When these proved capable of meeting all the requirements of the proposed system, Dr. Arnold was satisfied and I heard no more about the use of the Colpitts amplifier for this purpose.

In 1930, Western Electric delivered 78 of the negative feedback amplifiers for a field trial of the system at Morristown, N.J. The test used a 25-mile section of cable containing 68 pairs, two terminal feedback amplifiers, and 68 repeaters. With this experimental equipment using all nine channels, it was possible to simulate two one-way connections between points separated by 7650 miles going through nine feedback amplifiers and 306 repeaters in each direction. The speech quality was excellent even though the total attenuation in each direction was about 12 000 dB. This huge loss was balanced by an equal amplification furnished by the repeaters accurate to a required precision of about 1 or 2 dB. Also, the overall significant voice distortion was additive—315 times that contributed by a single repeater. Finally, it is intriguing to recall that each amplifier occupied a 19-inch panel and had a $\mu\beta$ path more than a yard long. The amplifiers in present coaxial cable systems are about $1/10\,000$ this size and have a feedback path about a millimeter long! Moreover, they will transmit 10 800 voice channels, while the most I was able to get, by 1940, was 12.

The successful completion of the Morristown test, in 1931, brings to an end the technical account of how the negative feedback amplifier was invented. In my first open publication on the invention (*Elec. Eng.*, vol. 53, pp. 114–120, Jan. 1934), I was able to report that "... by building an amplifier whose gain is made deliberately, say 40 decibels higher than necessary (10 000-fold excess on energy basis) and then feeding the output back to the input in such a way as to throw away the excess gain, it has been found possible to effect extraordinary improvement in constancy of amplification and freedom from nonlinearity."

Within a few years, Harry Nyquist would publish his generalized rule for avoiding instability in a feedback amplifier, and Heinrich W. Bode would spearhead the development of systematic techniques of design whereby one could get the most out of a specified situation and still satisfy Nyquist's criterion. Through their work, as well as the efforts of many others, the feedback amplifier was launched on the road that within 25 years would lead to a report by Dr. Kelly that "the negative feedback principle is now applied almost universally to amplifiers used for any purpose."

Nine years in the Patent Office

Although the invention had been submitted to the U.S. Patent Office on August 8, 1928, more than nine years would elapse before the patent was issued on December 21, 1937 (No. 2 102 671). One reason for the delay was that the concept was so contrary to established beliefs that the Patent Office initially did not believe it would work. The Office cited technical papers, for example, that maintained the output could not be connected back to the input unless the loop gain was less than one, whereas mine was between 40 and 50 dB. In England, our patent application was treated in the same manner as one for a perpetual-motion machine. The British patent office also claimed the amplifier would not work and asked me to submit a working model! Harry Burgess was eventually able to overcome all these objections by submitting evidence that 70 amplifiers were working successfully in the telephone building at Morristown. But this process took several years.

The second reason for the nine-year wait was that numerous Patent Office objections to the length and arguments about the claims had to be resolved. The patent consisted of 42 pages of text, nine pages of 126 claims, and 33 pages depicting 75 figures, many of which were complicated. The extraordinary length of this application was attributable to the fact that as the invention was in a new field whose principle was not understood, the patent had to teach a new art: the negative feedback amplification principle.

I wrote most of the body of the patent, supplied all the illustrations, and suggested most of the claims. I foresaw that the mathematical understanding developed in connection with feedback electronic amplifiers could be carried over and applied by analogy to the synthesis and analysis of other kinds of amplifiers, to all kinds of control systems—mechanical, acoustical, chemical, hydraulic, or whatever. The patent clearly applies to large complex industrial and military control systems, implying the capability to exercise specific control of a single variable or an entire system.

To achieve these ends, the claims were written very broadly and I worked tenaciously with the U.S. Patent Office to keep the broad applicability as granted, even though this added to the delay.

On the 50th anniversary of the invention, it is gratifying to me to observe that negative feedback amplifiers and the feedback principle have found many new applications to all types and forms of communication systems—underground, underwater, in the air, via satellites, in outer space. Equally important is the application of negative feedback to a rapidly growing number of unrelated diverse fields including, though not restricted to, biomechanics; bioengineering; cybernetics; computers; artificial limbs for the disabled; most of the equipment and instruments currently used by nurses, physicians, and surgeons; and new consumer products. ◆

Harold S. Black (F) is best known for his invention of the negative feedback amplifier, described in this article. For this and other technical achievements, including contributions to the theory and application of pulse-code modulation, he was awarded the Lamme Medal in 1957. Among his many other honors is a U.S. War Department Certificate of Appreciation for his work during World War II. He began his career in 1921, after his graduation from Worcester Polytechnic Institute with a degree in electrical engineering, by joining the Western Electric department that later became part of the Bell Telephone Laboratories. He remained with Bell until 1963, when he became a Principal Research Scientist with the General Precision Corporation. Since 1966, he has been a communications consultant. Dr. Black is the holder of 62 U.S. patents and 271 patents in 32 other countries, as well as the author of a number of technical papers and, in 1953, of the definitive book, *Modulation Theory*. He received the honorary degree of doctor of engineering from Worcester Polytechnic in 1955.