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Negative Feedback, Amplifiers, Governors, and More

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The invention of the negative feedback amplifier by Harold S. Black (1898–1983) in 1928 is considered one of the great achievements in electronics. In fact, it is listed among the IEEE Milestones, where it is credited to Bell Labs. Black was hired by Western Electric in 1921 and assigned to work on the Type C system, a newly introduced three-channel telephone network whose push-pull, vacuum-tube, repeater amplifiers produced too much harmonic distortion when connected in tandem [1]. At that time, telephone networks were spreading, and Bell Labs emerged quickly as the major research company in the telephone industry. The extension of lines over long distances required counteracting signal attenuation, which occurred, though at a reduced level, even in lines provided with Pupin's loading coils, which discretely increased the line longitudinal inductance L so as to match the Heaviside condition $L/R=C/G$ for distortionless transmission (R being the longitudinal resistance and C and G the transverse capacitance and conductance, respectively).

The idea of the repeater amplifier had developed from the well-established telegraph technology in which line attenuation was counteracted by the placement of repeating stations, consisting of batteries and relays operated by the weakened arriving signals, at regular distances. These regenerating stations allowed telegraph signals to travel overland as far as needed. This technology was developed in the 1830s by Joseph Henry (1797–1878) and Samuel Morse (1791–1872) and was very successful against the attenuation of telegraph digital signals.

Telephone lines, which started to be laid in the 1880s, were also prone to attenuation. However, their signals were analog, so regeneration based on just an electrochemical battery and an electromagnetic relay could not be used. Early devices trying to regenerate telephone analog signals consisted of pre-electronics crude amplifiers [2], but the real step forward occurred after the invention of the vacuum triode, namely, Lee De Forrest's Audion, in 1906 [3].

EARLY DEVICES TRYING TO REGENERATE TELEPHONE ANALOG SIGNALS CONSISTED OF PRE-ELECTRONICS CRUDE AMPLIFIERS.

During the first decade of the 20th century, a number of prolific inventors formulated its use as a signal detector, a rectifier, an amplifier, and a high-frequency oscillator. However, vacuum tubes were costly, also in terms of supplying batteries, due to high power demand. It was desirable that a high gain be provided by a single device. A solution was found in 1912 by Edwin Armstrong (1890–1954), then an undergraduate student at Columbia University. He conceived the regenerative receiver of wireless signals—an amplifier provided with partially positive feedback in which a part of the output signal was fed back. In this way, the signal was amplified hundreds of times by a single device [4].

The system was patented in 1914 and was later the object of a long and bitter litigation with Lee De Forest (1873–1961), the holder of a similar patent of 1916. In the final courtroom battle in 1934, the Supreme Court ruled in favor of De Forest. Meanwhile, in 1922, Armstrong introduced the superregenerative receiver, which used a larger part of the signal to obtain an even higher amplification (gain around 1 million). All these forms of positive feedback could provide a high gain, high selectivity, and high quality factor.

Electronic amplifiers were soon used also as repeaters for regenerating long-distance cable telephone signals. Within such a program, Harold D. Arnold (1883–1933) of Western Electric developed an improved high-vacuum triode in 1913 that was used in the 2,900-km transcontinental line connecting New York and San Francisco, laid down by AT&T in 1914 and put into service the following year [5]. However, in this case, narrow bandwidth involved poor linearity.

The Western Electric Type C system of 1921 was an advanced solution for telephone networking that required several repeater amplifiers in tandem. Unfortunately, this arrangement resulted in an unacceptable harmonic distortion, and Black was appointed to search for a solution. When Bell Labs was consolidated in 1925, by merging Western Electric Research Labs and part of the research department of AT&T, Black was engaged in finding measures for improving the linearity and stability of such repeater amplifiers. The requirements were, by far, well beyond the limits of the technology of the time.

After six years of persistent search, during which he benefited from advice from coworker Ralph Hartley (1888–1970) and attended an inspiring lecture by Charles Steinmetz (1865–1923), Black conceived the groundbreaking idea of the negative feedback amplifier one morning in August 1929, while he was riding the Hudson River Ferry to work. (Figure 1) [6]. By December, he had fully demonstrated the soundness of the concept by achieving, in a single amplifier, a distortion reduction of 100,000 to 1 (50 dB) over a bandwidth of 4–45 kHz. Tandem tests were performed in early 1930 on a system simulating a 12,000-km connection. The test showed an excellent speech quality, with an attenuation of about 12,000 dB, balanced by repeaters.

A patent was required in 1928 and released in 1937 [6]. Black's negative feedback was seminal to subsequent work done at AT&T by Harold Nyquist (1889–1976), who developed the stability criterion for feedback systems in 1932 (Nyquist's stability theorem) [7], and at Bell Labs by Hendrik Wade Bode (1905–1982), who conceived the eponymous diagram in 1938 that allowed taking full advantage of Black's invention [8]. These studies constituted the foundation of information theory, developed in the following years mostly at Bell Labs and AT&T by Nyquist, Bode, Hartley, and others, up to pivotal contributions by Claude Shannon (1916–2001) in the years 1938 and 1948. Frederick Terman (1900–1982) of Stanford University was among the first to use the negative feedback principle in electronics since 1939. William R. Hewlett (1913–2001) and David Packard (1912–1996), two of Terman's most brilliant students, designed their audio frequency oscillator 200A based on negative feedback, starting the rise of the Hewlett-Packard Company [9].

A general definition of negative feedback was given by Norbert Wiener (1894–1964) in his seminal book *Cybernetics* of 1948, in which he specified that negative feedback occurs when "the information fed back to the control center tends to oppose the departure of the controlled from the controlling quantity" [10]. As a matter of fact, the negative feedback amplifier played a key role in the success of the long-distance telephone and television network. And the application of the negative feedback has not been limited to telecommunications. Industrial and military applications as well as servomechanism and drives use it widely. Negative feedback formed the basis of early operational amplifiers. It has been used in biomechanics, bioengineering, cybernetics, computers, artificial limbs, and many other devices. The transition to solid-state electronics even increased its importance. Both electrical and mechanical controls have largely grown on the concept of negative feedback. It is exploited in psychology, physiology, sociology, and ethology, namely in studies on the behavior of the brain, living beings, animal flocks, and human societies [11].

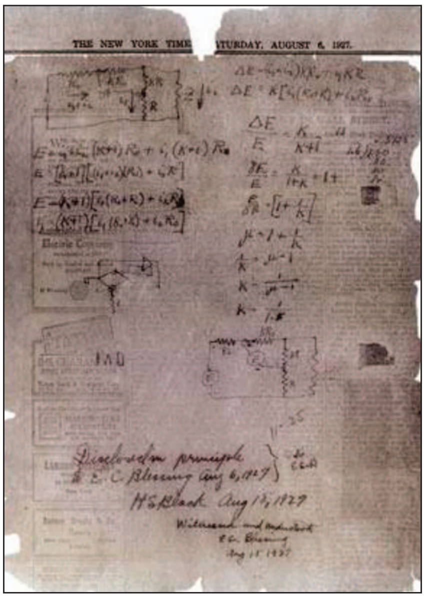

FIGURE 1 – The page from the *New York Times* on 2 August 1927 in which Black sketched his early ideas on the negative feedback amplifier. (Photo courtesy of Guillermo Carpinter.)

However, Black was not the first to exploit the concept of negative feedback. In 1788, at the dawn of the industrial age, James Watt (1736–1819) invented the centrifugal governor for regulating in a negative-feedback scheme the steam input and, thus, the engine shaft speed, preventing run away (Figure 2) [12]. He was inspired by a similar device already used in windmills to regulate the distance between millstones, although not on the feedback basis.

In 1840, Astronomer Royal George Airy (1812–1878) developed a feedback-controlled motor for a Greenwich telescope to compensate for the rotational motion of the earth. The design was based on differential equation analysis. An early general study of feedback control was proposed in the 1868 paper "On Governors" by James Clerk Maxwell (1831–1879), which discussed Watt's centrifugal governor and other devices by engineers and technicians of the day [13]. The theory was further developed by other control pioneers, notably English-Canadian Edward John Routh (1831–1907), German Adolf Hurwitz (1859–1919), Russian Aleksandr Lyapunov (1857–1918), Slovakian Aurel Stodola (1859–1942), and the great French mathematician Henri Poincaré (1854–1912). It seems that if one wanted to become a control pioneer, it was convenient to be born in the 1850s!

Despite extensive exploitation during the Industrial Revolution, negative feedback existed much earlier. The first device that reportedly exploited

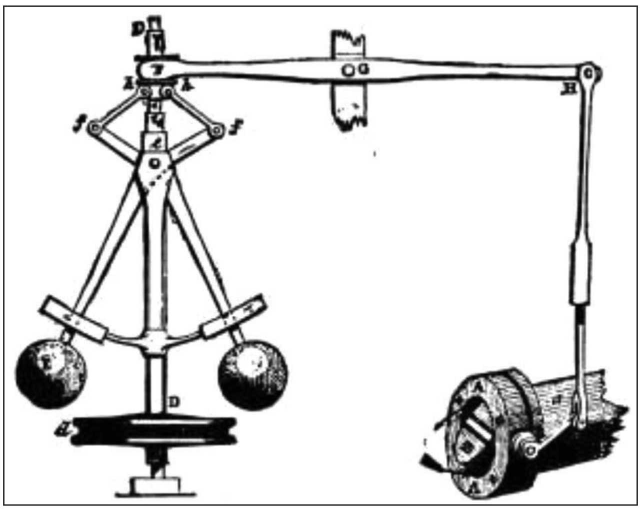

FIGURE 2 – The centrifugal governor was invented by James Watt in 1788. It was the first industrial implement exploiting negative feedback. (Image courtesy of Wikimedia Commons.)

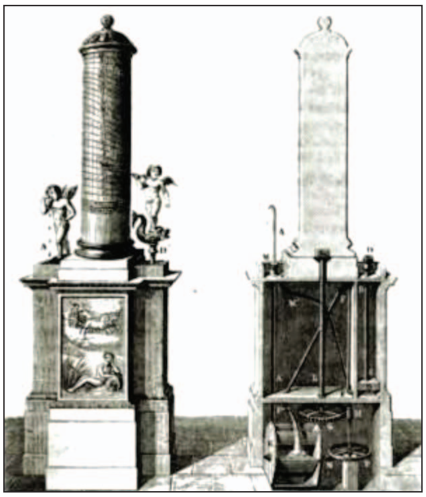

FIGURE 3 – The advanced water clock made by Ctesibius in the third century BCE as visualized by a 17th-century author. It was the first documented device that included a negative feedback mechanism. (Image courtesy of Wikimedia Commons.)

the principle was a water clock built by the great Greek engineer Ctesibius in the third century BCE. It was a technological marvel of that time (Figure 3). In the third century AD, Chinese engineer Ma Jun built the south-pointing chariot that also exploited the concept in its differential gearing for maintaining its pointer in the initial direction, regardless of the path taken [14]. In the early 13th century, Islamic engineer Al-Jazari made several mechanisms (a candle clock, a flushed wash basin, and an elephant clock) that used the negative feedback principle [15]. In the modern era, Dutch engineer Cornelis Drebbel (1572–1633) invented a chicken incubator with a mercury thermostat that feedback-controlled the temperature [16]. The fantail patented by Edmund Lee in 1745 was a small wind wheel that feedback-controlled the blade orientation in smock windmills to direct it against the wind [17]. The bimetallic stripe used by John Harrison (1693–1776) in his revolutionary H4 marine chronometer of 1761 to compensate for thermal variations also resorts to negative feedback.

Considering this historical evidence, we can hardly attribute the invention of negative feedback to Harold Black. Instead, he conceived its use in the electronic amplifier, which resulted in a quite revolutionary device. It was a very fruitful and timely invention that arrived when electronics was on the way to becoming a dominant technology. In Black's years, technology had greatly advanced compared to the epoch of Watt, Aires, and Maxwell, and the times were mature for exploiting at a larger level the benefits of the feedback concept.

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