Norbert Wiener and the Age of Controls, Communications, and Cybernetics—Animal and Machine—in Electrical Engineering

By Marcelo Godoy Simões

ELECTRICAL ENGINEERS study dynamical systems, which evolve throughout time in a deterministic way. Most often, they are modeled based on the laws of physics, chemistry, science, mathematics, and economics; however, it is possible to model on previous data or heuristic rules. Engineering and technology is about comprehension and understanding. We want to know the flow of electricity, motion of a car, what keeps an airplane flying, how electrochemistry in a battery works, how hydrogen goes through a membrane in a fuel cell to produce electricity and heat, and so on. We also want to know about the balance of systems as well, how a population of wolves would stabilize an ecosystem, how goods and prices are related in an economy based on inflation, how ballast and air pressure would keep a submarine under water, and so on. The concept of feedback for single-input, single-output (SIMO) or multiple-input, multiple-output (MIMO) problems were front and center throughout the 20th century. After closed-loop control and stability were approached, there was an enhancement of understanding biological processes, medicine, psychology, social sciences, even agriculture, farming, and many other fields. The level of glucose in humans is now understood by medical doctors as negative feedback: when the glucose level is high, the pancreas releases insulin to make the sugar level in the blood decrease. And health-care providers evaluate equilibrium in several blood test data analyses to understand how substances in the blood, such as oxygen, calcium, sodium, potassium, and the number of red and white cells, are related to blood pressure, heart beats, and pupil dilation and how breathing is interrelated in the homeostasis and equilibrium of life conditions. Negative feedback has become the way to evaluate. Any positive feedback may indicate problems, requiring the short- or long-term need for interventions, precautions, and avoiding collapse situations for humans, machines, processes, and nuclear power plants.

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The Emergence of Feedback

In the first few years of the 20th century, EE was not yet established. Therefore, few principles were known about how feedback could enhance telegraphic and radio transmission. Amplifiers made from new vacuum tubes could be stabilized for operation with feedback. Such concepts were initially developed by James Clerk Maxwell, who became interested in another James' work—James Watt (1763–1819)—who controlled a steam rotating machine with a valve commanded by a flying ball with two arms, a kind of a pendulum adapted for actuation on the steam inflow. Watt also developed intriguing closed-loop mechanisms, approximating straight lines with rotating joints; they are still useful for designing walking and hopping robots, linear haptic interfaces, origami-based mechanisms, and deployable linkages. Historically, mechanical engineers have worked on these linkages, converting rotary motion to a linear one, initially in steam engines. The synthesis of four-bar linkages has been of interest to industrialists (prequel engineers) since the 1800s due to its simple architecture and rich design space; for example, a pumpjack's main mechanism (a reciprocating piston pump in an oil well) is a four-bar linkage.

Maxwell became interested in studying the rings of Saturn and thought about applying such understanding to mathematically analyze speed controllers, particularly approaching the operation of Watt's flying-balls rotating actuator.

The Elektron Whisperer

Feedback Amusings and Thoughts

My ancestors were fishermen from rural areas who were familiar with rivers and the ocean in the state of São Paulo (Brazil). When I was a kid, I used to go fishing with my father, uncles, and cousins. My grandmother sometimes joined us, fishing in rivers, lakes, reservoirs, and on the sea. We used to go to Santos, a famous city that made Pelé famous when he played for the local football team. We hired a boat pilot to take us fishing, mostly at the end of the day, sometimes spending the whole night. I remember observing how the helmsman would steer the boat, starting with a slow engine speed. After the shore waves, the engine would be full blast. He would be looking at the horizon, a destination farther than the curvature of the earth. To me it was magical how he knew the path, and by just shifting the rudder left and right, we would arrive at our destination. Sometimes the ride was as quick as 15 min; in some places, we would have to go by boat for almost an hour. Adult explanations were conjectures about the compass; looking at the stars, a fisher would know the waters. Fisherwoman, fisherfolk, and fisher are all same as fisherman, and any gender who fishes is not really concerned with pronouns when fishing. There was no GPS at that time. Big boats would have a nautical chart, but the small ones who we used to take, not even a map, all was in the mind of the pilot. And my nine-year-old self was puzzled by how just moving the rudder with simple lefts and rights would put us on a path to arrive at our destination.

In seventh grade, I definitely knew that I loved math and science. So I started to pay attention to the basics of electricity, radios, TVs, how the electric shower worked, and I even opened the back of our RCA Victrola, which mesmerized me with its glowing vacuum tubes and the smell of heat in that wooden structure. My cousin, an electrical engineer, explained many things to me, and he told me some interesting ideas about control systems. I tried my best to understand, but the concept of feedback as it related to how the rudder was moved left and right was still not clear. He gave me an example of how the water reservoir in my house controls the amount of water, but at the same time discussed the temperature of the shower.

Somehow, I grasped that steering a boat could be conceptualized and that commanding the rudder was a correction. To me that was new: the helmsman compared an imaginary straight line along the boat, and looked for something he knew as a mark; it could be a rock, an island, at night it could be a star. The trajectory of the boat should be adjusted by a difference, little pluses and minuses, of the deviation from a mark compared to the straight line of the boat's main axis. The rudder moves away the water under the boat, making a higher pressure on one side, pushing the back of the boat to the right or left. This was what my cousin said was a closed-loop control, but in other situations, he was also talking about closed-loop control, for example, about the tuning of a radio on the dial. I was 13 years old, how could I possibly understand the math and physics behind these concepts?

As I got older, I read more electronics magazines to try to learn about audio amplifiers. I kept noticing the concept of "feedback," "realimentação," in Portuguese. During the second year of my bachelor's degree studies, I was admitted to the Electrical Engineering (EE) Department, and in my third year I started electronics course work. I was learning about theories and laboratory experiences and became fascinated with radio and TV circuits. I learned about oscillators, transistors, and amplifiers. Using feedback was how the circuits were improved.

In the fourth year of my engineering studies, I had strong engineering- and math-focused courses on control systems, linear systems, signals, and processing, which made a further impact on me. During my fifth and final year of studies, I decided to move to the telecommunications area because it had more analog control and transistorized circuits for high-frequency applications. By then, I had the maturity to look back at my 13-year-old self. Therefore, when I was a young engineer, I realized how a fishing boat pilot could steer toward a place on the ocean to spend a night fishing and how closing the loop could be accomplished. Things flipped in my mind when, for the first time in my 10 semesters in EE, I took a course on power electronics, which defined my career.

Then in the 1990s there was a TV ad from Mercedez Benz about their advanced car suspension technology, with chickens keeping their eyesight when moved up and down, left and right, jerked, people would then believe how Mercedez Benz would have "awesomely chicken-level standards" embedded in their car technology. In this article, I discuss how control systems, starting with Maxwell, became elevated in shaping our 20th century through cybernetics—with the geniality of Norbert Wiener.

—Marcelo Godoy Simões

He wrote a 14-page paper, "On Governors," on 20 February 1868, and it was quickly published in March of the same year. He made an analysis of a driving power (P) and a given load torque, defined in the article as *resistance* (R), which was the resulting shaft motion on a viscous fluid or air, a dragging force that opposes the motion of such a shaft. Applying Newton's laws on a rotating shaft, he wrote the equations for a necessary effort (F) to change the angular velocity (V) on such a shaft, such as F(dx/dt–V). Then, he assumed a typical valve or governor that regulates the keeping by the second-order derivative of the angular velocity multiplied by the moment of inertia, balanced by the driving power P, which was subtracted from the viscosity, or dragging effect (R), minus the amount of needed driving power quantity F(dx/dt–V). Therefore, if P is increased or R is diminished, the velocity will increase, and the opposite as well. By making assumptions of such a velocity to be desired to settle down in equilibrium, he discussed a possible steady-state error from the input reference, also assuming disturbance on the driving power, or further dragging probably proportional to the speed. In such a paper, he evaluated, from simple to more complicated structures, also describing a liquid in a tube revolving about a vertical axis. His formulation is easy to be understood today as a baseline for a state-space synthesis, maybe for a possible pumping up water for a reservoir, perhaps indicating that he was thinking of some kind of pumped hydro type of energy storage, but not clearly pointed out as such. He described based on mechanical systems terminology; he called regulators and moderators, mentioned enhancements invented by Jenkin and used by Siemens, with a centrifugal rotating piece, containing an appendage of a loose wheel, which would maintain the rate of correction. Such an appendage would keep an internal energy stored, proportional to the integral of the error in the set point.

In his mathematical formulation, Maxwell defined how a set point applied to a negative summer (with negative feedback) would make the proportional and integral (PI) or the error of velocity to drive the shaft, establishing the principles of PI control, which is the basic foundation block of control systems. He did not use any block diagram, just mathematical descriptions. He continued further in his article, making combined differential equations; arriving to a third order, also simplifying a fourth order to become third order; approaching possible exponential responses; and assuming the roots of such a cubic polynomial. By page 10 of the 14-page article, he found necessary conditions for stability. But he was not sure if those conditions would be sufficient for really making the system stable. But in such a seminal work, Maxwell placed stability as the core of his analysis, making a distinction of moderators, where the correcting torque would be proportional to speed error. On the other hand a governor would also contain a term proportional to the integral of the error. He observed mathematically that exact speed regulation, with zero steady-state error, was possible when minimizing the integral of the speed error, with a linearization of the equations of motion through the determination of the algebraic solution of the roots of a polynomial, which is now called A *characteristic polynomial*. He mentioned that it should have negative real parts, similar to his investigation on Saturn's rings, which were possibly based on the work by Edward Routh, who provided a solution that today is called a *Routh–Hurwitz stability criterion*. This was the birth of PI control, in a paper written by J. Clerk Maxwell. But it became overlooked because Maxwell made further-and-beyond impact in electromagnetism, with his original equations of electromagnetic fields; those became synthesized through a new formulation of multivariable calculus and operators by Oliver Heaviside. Albert Einstein was already alive, and too many scientific and engineering discoveries were happening in a slow-paced communications world, as opposed to our current one.

Cybernetics Arising

Wiener decided to use science and technology to win World War II (WWII). He made it possible that humans and systems could be tackled in a multidisciplinary approach. Radars could detect attacking airplanes, but as soon as the detection was available, the planes would be in an unexpected position. Then he did many experiments, interviewed pilots and military personnel, and brought together behaviorism in a mathematical formulation. His algorithm, now called the *Wiener filter*, would predict where those planes most likely would be after detection, also considering the delay in the reaction. He is the father of what we today call *control systems*, although his original perspective was more encompassing through a signals/systems/math/behavior umbrella. He presented an unifying perception of circuits, control, communication, and information theory in his 1948 book, *Cybernetics, or Control and Communication in the Animal and the Machine*; a theory of everything, based on systems, inputs, outputs, information flow, noise, stability, feedback, triggering to influence the next three or four generations of academics, researchers and scientists—a scheme for predicting the future, as best one could do, on the basis of incomplete information about the past. It was statistical in nature with modeling information for removing noise.

His approach was based on earlier work on integral equations and Fourier transforms—becoming the foundation of random processes and stochastic systems. Wiener baptized the emerging field of control and communication as cybernetics from the Greek cυβερνη'της, such a "cybernetics" is derived from the Greek "kubernetes," translated as "steersmanship," meaning the understanding and skills required to successfully steer a ship to a desired destination. Therefore, my young self-curiosity on how a pilot driving a boat, correcting the rudder with little movements, eventually shows as the core of the original name by Wiener on control systems after all. Wiener made "cyber" a part of our daily contemporary life. The concept became an ever-encompassing term: from cybernetics, to cyborg, then, cyber robotics, cyberspace, cyberculture, cyberpunk, cyber-physical systems, and cybersecurity. In addition, there are terms such as *cybernating*, *cyberdating*, *cybercafe*, and *cybersex*. It has been the most enduring, and comprehensive multidisciplinary terminology; a trend of words in Google shows an exponentially increasing presence for the past 85+ years.

During WWII, Wiener's work on automatic aiming and firing antiaircraft guns motivated him to investigate information theory done independently of Claude Shannon (who also deserves a narrative of his own contributions). The Wiener filter was initially published in 1942 as a classified document, supporting modeling and estimation to minimize the noise present in a signal by comparison with a model reference of a desired noiseless signal. To predict the position of German bombers from radar reflections, it was required to forecast the new position. By the time the shell reaches the vicinity of the target, the target would have then been moved or changed directions; Wiener considered the muscle responses of pilots and interviewed pilots to have scenarios on what would be their next decision immediately after being detected. He blended information and control in a way that would make the dawn of cybernetics, upscaling basic feedback previous ideas. It is part of lore that American guns fitted with Wiener filters, shot down 99 out of 100 German bombers as they entered Britain from the English channel on their way to London, but is not possible to ascertain such an efficiency.

Wiener acknowledges that Maxwell was the father of control principles; proportional-integral-derivative (PID) control is still taught as a significant concept in contemporary engineering. With the increasing opening of new EE departments after WWII, modern automatic control, state-space oriented, multivariable control systems, and classic and modern controls were established from 1950s to the 1980s. For students in electrical and electronics engineering, it became an intertwined area of math, signals, systems, and digital algorithms. Education and research on this area has been influential for all generations, supporting the notion that electrical engineers should be capable to design, even with only pencil and paper, compensators such as PID lead, lag, and lead-lag. Most of the textbook classic problems would be about SIMO control structures, the classic design based on Nyquist, Bode, and root locus. However, when MIMO using a state-space approach became widely adopted, most of the advanced curriculums covered advanced mathematical concepts and nonlinear systems.

Control Systems in Electrical Engineering

Books and courses have been published since the 1950s to help students understand how a suitable closed-loop controller can be designed, analyzed, and built, initially based on analog control. With primordial mainframes, desktops and microprocessors in the 1970s were made for people to discretize control laws, using Euler's straightforward trapezoid methodology, then other methodologies. Some theoreticians would prefer the utilization of z-transforms, although they are not necessary for practical implementations. Typically, control systems use a fundamental approach for the mathematical description of closed-loop properties in terms of open-loop characteristics. It also incorporates a main plant or main system model, based on ordinary differential equations, Laplace transforms, and frequency domain. From basic principles, it is not very difficult to define disturbance rejection properties, steady-state error performance, sensitivity, and parameter variation. Good control systems designers also know how to incorporate feedforward or mitigate right-half-plane zeros, nonminimum-phase systems, and industrial processes with transport delay for analog or digital implementation.

After WWII, Wiener became famous. He helped the Massachusetts Institute of Technology (MIT) to recruit a group in cognitive science, and researchers in neuropsychology, mathematics, and biophysics of the nervous system. Warren Sturgis McCulloch and Walter Pitts joined MIT and became the fathers of artificial neural networks. They made pioneering contributions to computer science and artificial intelligence. The McCulloch and Pitts paper is the inception of two fields: the theory of finite-state machines as a model of computation as well as the field of artificial neural networks, which has been rebranded in the past few years as deep learning.

The history of neural networks and fuzzy logic could be the subject a future article. But it is important to have a parenthesis here as neural networks, inspired by studies for understanding the biological nervous system, has a first relevant reference on the physiology and psychology studies related to the structure and function of the brain, published by William James. After McCulloch and Pitts published their seminal paper in 1949, Donald O. Hebb published a book as Hebbian learning. In 1958, there was a landmark paper by Frank Rosenblat that defined a neural network structure called a *perceptron*, simulated on an IBM 704 computer at the Cornell Aeronautical Laboratory and, for the first time, it became known that such a perceptron could be a "leaning machine." In 1960, Bernard Widrow and Marcian Hoff published a paper in which they simulated neural networks in computers, and also had their designs implemented in hardware. Widrow and Hoff introduced a device called an *adaline* (for adaptive linear). An adaline consists of a single neuron with an arbitrary number of input elements that can take on the values of plus or minus one and a bias element. Before being summed by the neurode summer, each input, including the bias, is modified by a gain. The Widrow–Hoff algorithm is a form of supervised learning that adjusts the weights according to the size of the error on the output of the summer.

In 1969, Marvin Minsky and Seymour Papert's book *Perceptrons* cooled off the neural network community at that period. Their writing style was acidic in claiming that most of the research about neural networks was "without scientific value." They showed that the two-layer perceptron was rather limited because it could only work problems with linear separable solution space. There was no effective algorithm for training a network with three or more layers until the derivation of the backpropagation algorithm later. After their book, virtually all the research funds for neural networks dried up. A revival in the field came with the research conducted by John J. Hopfield in the beginning of the 1980s, leading to today's Hopfield network, also Cerebellar Model Articulation Controller by J. Albus, and the Teuvo Kohonen self-organizing map with unsupervised learning models initially published in 1982. What primarily influenced people about the capabilities of neural networks was the discovery of the backpropagation algorithm. It was found by Paul Werbos, Dave Parker, and independently rediscovered and popularized around 1985 by Rumelhart, Hinton, and Williams. Neural networks had a second birth in 1985.

Wiener developed the theories of cybernetics, robotics, computer control, and automation. He was so advanced in his ideas that he wrote about modeling of neurons to John von Neumann, documented in a letter dated November 1946, with his theories and findings with other researchers, on such an encompassing cybernetics approach. Wiener included Soviet researchers in his correspondences. One important one was Andrey Kolmogorov, who published a paper in 1938, establishing theorems for smoothing and predicting stationary stochastic processes. They developed mutual interest on studies of systems capable of receiving, storing, and processing information to use it for control, even helping with setting up neural networks' initial foundations. Obviously, during the Cold War, Wiener's acquaintance with Kolmogorov caused suspicions by the U.S. government, which were typically orchestrated by the U.S. Federal Bureau of Investigation's director in charge during that time. Wiener was a strong advocate of automation to improve standard of living and to end economic underdevelopment. His ideas became influential in India, whose government he advised during the 1950s.

After the war, Wiener became increasingly concerned with what he believed was political interference with scientific research and the militarization of science. His article, "A Scientist Rebels," from the January 1947 issue of *The Atlantic Monthly* urged scientists to consider the ethical implications of their work. After the war, he refused to accept any government funding or to work on military projects. Wiener's beliefs concerning nuclear weapons and the Cold War contrasted with those of von Neumann. The advent of cybernetics made psychological and behavior approaches in neural networks spin off and augmented the rise of cognitivism. Then, scientists in different areas considered internal states of mind, thoughts, and consciousness. Multidomain linguistics such as Noam Chomsky, plus the emergence of neural sciences, brought mathematics, biology, social sciences, medicine, and technology. Conferences, meetings, publications, summer schools, symposiums, and research centers became established toward the end of 1990s.

Cybernetics Approaches: Mathematics, Engineering, Computer Sciences

Wiener filter mathematics was a reference for the Kalman filter, applied for advanced problems. In about the same time, a young professor, Lotfi Zadeh, coauthored with Charles Desoer, *Linear System Theory: The State Space Approach*, with foundations for system analysis and control. Rudolf Kálmán was a colleague in the same university as Zadeh—Kálmán enhanced and improved the Wiener filter, the Kálmán filter would

> Cybernetics, which was a theory of everything, inverted from the inside out to become an everything through a theory, an interplay of technology, society, and the environment, approaching complex systems through processes like feedback and communication, engineering systems, and systems engineering.

require in-depth mathematical modeling—Zadeh soon realized that another direction would be effective by assuming that the more complex a problem gets, the more uncertain becomes the parameterization and modeling, to the point of not no longer having a physical meaning in all the mathematics. Therefore, cybernetics-Zadeh thought about computing with words. He wrote a seminal paper in 1965 on fuzzy sets, showing how to replicate human-like reasoning and heuristics and giving birth to the mathematics of fuzzy set, which became the theory for fuzzy logic control and fuzzy modeling. It is a different path of theoretical mathematics for modeling systems for designing a control. It is based on modeling how human operators with rules of operation, or data from previous control batches, could be used to design a rule-based algorithm instead of a mathematical compensator.

Catherine Everit Macy Ladd was an American philanthropist who founded and endowed the Josiah Macy Jr. Foundation in honor of her father. Cybernetics conferences were held between 1946 and 1953, motivated by Lawrence K. Frank and Frank Fremont-Smith of the Macy Foundation. McCulloch was the chair of this set of conferences and was responsible for ensuring disciplinary flow. The cybernetics conferences were particularly complex as a result of bringing together the most diverse group of participants of any of the Macy conferences. The principal purpose of these series of conferences was to set the foundations for a general science of the workings of the human mind, organized studies of interdisciplinarity spawning breakthroughs in systems theory, cybernetics, and what later became known as *cognitive science*. Wiener knew that it was important to have a wide variety of experts, so he engaged in yearly conferences called *Macy meetings*. During these meetings, participants sought interactions in the fields of anthropology, linguistics, mathematics, computation, sociology, psychiatry, psychology, neurology, and biology.

We currently have many scientific computational platforms. Students click and drag, point and press enter, select menus, and blindly make model reference and parameter estimation for control applications in routine school homework. Our current generation is probably already taking for granted the depth and beauty of cybernetics, systems, and the control approach. As we admire “influencers” (social media providers of content), maybe we should also think of Wiener: the major analog and digital influencer. There have been scores of thousands to millions of people who have learned and used the theories developed by and after Wiener. We have to be aware that control systems, as an area of expertise is not yet 100 years old.

Cybernetics is alive and well, understanding technologies and their interactions with society and the environment. We now need a sustainable society, solutions for smart and cheap electricity, electric mobility systems, water systems, food cycles, and upscaling based on a market not dominated by multinational control. Let us work to mitigate gender and socioeconomic inequalities. Today, cybernetics is associated with how the circular economy aligns sustainability toward a fair context. Wiener envisioned a motivation for the next generation to move forward and upward: change is always a constant.

> Cybernetics looks at the design and development of renewable energy systems like hydropower or battery storage and seeks to uncover the impact on groups and environments that may have been outside the initial system design.
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> —*Prof. Katherine Daniell*, School of Cybernetics, Australian National University
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> Thank you for reading “The Elektron Whisperer” (TEW) column by Marcelo Godoy Simões. See you next time.

For Further Reading

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Biography

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