The Mathematician Who Revolutionized Engineering*

Norbert Wiener and His Stochastic Cosmos

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This article is based on a lecture given by the author at the *IEEE 3rd Conference on Norbert Wiener in the 21st Century*, held virtually at Anna University, Chennai (India), in July 2021. The article describes the personality of Wiener—both his mathematical skills (by focusing on the prediction problem) and his vision of science (through cybernetics).

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Prelude

This article is based on a lecture given by the author at the *IEEE 3rd Conference on Norbert Wiener in the 21st Century*, held virtually at Anna University, Chennai (India), in July 2021. The conference was planned as a part of the 225 years celebrations of the College of Engineering, Guindy Campus of Anna University

The lecture was part of a panel session (given on July 22nd) entitled *Norbert Wiener: Technology as a Social Change Agent*, with three invited speakers, Professor Heather Love (University of Waterloo, Ontario, Canada), Professor Junzo Watada (Waseda University, Japan) and the author. The organizer of the panel was Professor T. V. Gopal of Anna University.

Introduction

The activity of Norbert Wiener (1894–1964) is characterized by a peculiar eclecticism, which makes him a special gem in the landscape of scholars of the past century.

Keywords
Prediction theory, cybernetics, control science.

Surveying his many contributions is not the purpose of this article;

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the interested reader is referred to [1]. Our modest aim is to illustrate how Wiener was able to tackle specific mathematical problems as well as to cultivate an innovative general vision of science. We focus first on a specific problem of great interest even in our days and then comment on Wiener's interdisciplinary vision of science.

The problem we shall consider is prediction, namely the problem of estimating the future value that a variable observed up to a certain time instant, say t, will take at time $t' > t$. A distinctive feature of the problem is that no a-priori knowledge of the data generation mechanism is assumed; in other words, the prediction has to be constructed without any information on the way the data are generated. This approach is often referred to as the *black box* approach since one cannot "see inside" the system generating the data, the box; one can see only data and nothing else.

Wiener was working at MIT—the Massachusetts Institute of Technology, close to Boston (USA). Thousands of miles away, completely independently, Andrej Kolmogorov (1903–1987), a professor at Moscow University, was also studying the prediction problem, see, e.g. [2]. This is why this theory is often referred to as the Kolmogorov–Wiener or simply the KW theory.

Some twenty years later, R. E. Kalman made a further significant contribution by resorting to state-space models (K theory). In [3], one can find a detailed presentation of both the KW and K prediction theories.

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Prediction theory is also ancillary to the process of constructing a model. Indeed, a dominant model identification method consists of tuning a model's parameters by minimizing the corresponding prediction error over an interval of observation [4].

Nowadays, prediction and identification are taught in many courses around the world. For instance, the author of this article has taught model identification and data analysis (MIDA) at the Politecnico di Milano (Polimi), Italy, for many years. Currently, his course is for computer engineering and mathematical engineering students and counts more than 600 attendees. If one considers all the MIDA courses at the Politecnico, the total number of students is over 1000. This author had the privilege of launching the MIDA course at the university way back in 1977, when there were only a dozen students.

As mentioned above, after discussing the prediction problem, we will comment more generally on Wiener's interdisciplinary vision of science, a vision involving both the world of machines and that of living organisms in a common frame. This peculiar vision led to the foundation of a new discipline, *cybernetics*, defined as the science of control and communications in the animal and machine, as the tagline of Wiener's book of 1948 reads [5]. In the middle of the last century, these new ideas were extremely innovative and drew an enormous amount of interest not only in the academic world but also in public at large.

Prediction Theory

During the Second World War, a main problem was the so-called AA (anti-aircraft) servo-problem, consisting in finding the appropriate control action of anti-aircraft artillery to hit an enemy airplane. This calls for a double prediction problem: on the one hand, predicting the movement of the aircraft to trace its future movement, and on the other, predicting the trajectory of the anti-aircraft missile so as to hit the aircraft in its exact predicted position. To deal with such a complex problem, a US defence institution, the NDRC (National Defense Research Committee), signed a contract with MIT entitled 'General Mathematical Theory of Prediction and Applications'. The responsibility of the contract was given to Norbert Wiener, a professor at that university.

The results of such a contract led to the celebrated report *The Extrapolation, Interpolation, and Smoothing of Stationary Time Series with Engineering Applications*. Initially classified, the report was eventually published by the MIT press in 1949.

This report took advantage of Wiener's previous studies, mainly undertaken in 1920–1930, during which Wiener analyzed the spectral representation of random processes. The results of such early studies are summarized in the landmark paper [6], where random processes are analyzed in the frequency domain. In 1957, during a visit to the Indian Statistical Institute of Calcutta, together with P. R. Masani, Wiener wrote the paper [7] with results close to those presented in the NDRC report under weaker mathematical assumptions.

Coming again to the NDRC report, we can observe that its title anticipates various keywords of primary relevance in today's scientific world. Among other things, the term time series pops up. Time series analysis is a field which has been mainly developed in the framework of statistics, starting from about the 1930s. A renowned reference book is [8], a book which was reprinted many times with refinements passing from one edition to the subsequent one. A time series is a sequence of data ordered in time. One of the typical objectives is forecasting the evolution of the sequence; hence it is obvious that time series analysis and prediction theory are strictly related.

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Curiously, Wiener's report on the NDRC servo problem is also known by the nickname 'yellow peril'. Probably, the word yellow refers to the colour of the cover of the report, while the word peril comes from the difficulty in reading it due to the advanced math tools used its the computations, see [9].

Note that, in his studies, Wiener considered uncertain systems in continuous time and resorted to math tools of measure theory, as described in [10].

Models and Errors

The role of models in science is a major leitmotif in Wiener's reflections. Already in 1945, together with his friend Arturo Rosenblueth, he wrote an inspiring paper [11], where the necessity of models in science is emphasized, as stated in the incipit:

"The intention and the result of a scientific enquiry is to obtain an understanding and a control of part of the universe. ... No substantial part of the universe is so simple that it can be grasped

and controlled without abstraction. Abstraction consists in replacing the part of the universe under consideration by a model of similar but simpler structure. The models formal or intellectual on the one hand, or material on the other, are thus a central necessity of scientific procedure."

Obviously, hoping that a model perfectly fits real data is utopian. Rather, one expects that any model is affected by some non-null prediction error, randomly evolving in time depending on the disturbance acting on the system under study. As George Box used to say: *"all models are wrong, but some are useful"*.

The question then is: *What are the desirable characteristics of the prediction error to conclude that the model is a fair description of the phenomenon under study?*

A widely accepted point of view is that the prediction error should be completely unpredictable. If this happens, then the system's dynamics have been fully captured in the model, and there are no residual dynamics in the error. The concept of a fully unpredictable signal has been formalized and studied by many outstanding scholars leading to the notion of white noise (WN). In a note submitted to the National Academy of Science in 1921, Wiener explained this concept using an analogy with a pushball in which a crowd is milling around. *In this way, we shall have an irregular motion in which what happens in the future will have very little to do with what has happened in the past.* This irregular motion is often referred to as Brownian motion; the white noise is sometimes seen as its derivative. However, as Wiener remarked in various papers, the Brownian motion is not differentiable at any time point. In [12], we read—*"In summary and neglecting Wiener's work in prediction theory, which will be discussed elsewhere, Wiener's most important contributions to probability theory were centred about the Brownian motion process, now sometimes called the "Wiener process". He rigorously constructed this process more than a decade before probabilists made their subject respectable, and he applied the process inside and outside mathematics in many important problems."*

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In the same way that Albert Einstein played a main role in diffusing the WN concept in the field of physics, Norbert Wiener had the merit of popularizing it in the world of engineering, see [1], page 77. More in general, Wiener had the merit of spreading stochastic notions in the world of engineering, traditionally a deterministic world.

Cybernetics

As we have seen, one of Wiener's main contributions is his book *Cybernetics*, published by MIT Press in 1948. It is organized into 8 chapters as follows:

I. Newtonian and Bergsonian Times
II. Groups and Statistical Mechanics
III. Time Series, Information and Communication
IV. Feedback and Oscillation
V. Computing Machines and the Nervous System
VI. Gestalt and Universal
VII. Cybernetics and Psychopathology
VIII. Information, Language, and Society

In 1961 a second edition of *Cybernetics* was published with two supplementary chapters:

IX. On Learning and Self-Reproducing Machines
X. Brain waves and Self-Organizing Systems

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In cybernetics, perhaps not surprisingly, prediction plays a main role. Chapter 1 starts with the comparison of two problems: predicting the movement of planets (Newtonian astronomy) and predicting the weather (meteorology). These problems have very different characters: for the first one, accurate predictions can be made centuries ahead; on the contrary, one cannot predict tomorrow's weather with accuracy, at least not with the same accuracy as for the astronomical trajectories of heavenly bodies.

As for the word cybernetics as the art and craft of steering, Wiener wrote: *"In choosing this term, we wish to recognize that the* *first significant paper on feedback mechanisms is an article on governors, which was published by Clerk Maxwell in 1868"*. Here, reference is made to the celebrated paper [13]. The role of Maxwell as a trailblazer of systems and control ideas is discussed in [14].

A precursor of *Cybernetics* is the article [15], published in *Philosophy of Science*. We should note that Julian Bigelow (1913–2003) was a pioneer in computer engineering who frequently collaborated with Wiener, while Arturo Rosenblueth (1900–1970) was a Mexican physiologist with wide-ranging scientific interests. By the way, *Cybernetics* is dedicated to Rosenblueth. This showcases the interdisciplinary approach typical of Wiener. A central theme of the 1943 article is the behavioristic method, namely the study of an object independently of its internal structure by considering only its external behaviour (*black box* approach) and its final purpose (teleology, meaning finality), by focusing on the way the object can communicate and interact. The keyword behaviour has been used in more recent days by Jan Willems (1939–2013) in his attempt to re-found the study of systems [16] free from any prejudices from the role played by the external variables, see [17].

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In 1950, a few years after the first edition of *Cybernetics*, Wiener wrote another book, *The Human Use of Human Beings* [18]. In its preface, one can read the motivation behind this new publication: *"Upon the publication of Cybernetics, some of my friends urged upon me that I should write a related book for the layman"*. The importance of the layman's understanding of advanced topics is a constant struggle for Wiener throughout his life. *The Human Use of Human Beings* is organized in twelve chapters as follows:

I. What is Cybernetics?
11. Progress and Entropy
III. Rigidity and Learning: Two Patterns of Communicative Behavior
IV. The Mechanism of Language
V. The History of Language
VI. The Individual as the Word
VII. Law and Communication
VIII. Communication and Secrecy in the Modern World
IX. Role of the Intellectual and the Scientist
X. The First and the Second Industrial Revolution
XI. Some Communication Machines and Their Future
XII. Voices of Rigidity

Wiener was a scientist of exceptional talent with a truly vast range of interests. If we wanted to classify him based on his field of study, we would, of course, say he was a mathematician. After all, he even gave his autobiography the title *I Am a Mathematician*. Nonetheless, he was also very interested in its applications. An especially notable case is that of the robot Palomilla (which means little butterfly or moth in Spanish). This was a small tricycle cart built in the 1940s at the Research Laboratory of Electronics at MIT under the leadership of the young researcher Jerome Wiesner (who would go on to become the president of MIT from 1971 to 1980). The goal was to demonstrate the effects of feedback, in particular, to show potential oscillating movements that might occur. As described in Chapter XI of [18], the goal behind these studies was to understand the failure of the nervous system that leads to Parkinson's tremor, which was explained as 'excessively large' feedback. During public demonstrations, the cart was sometimes covered by a case shaped like a butterfly, which led to the nickname Palomilla.

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Among the many authors who took inspiration from the ideas of cybernetics, a celebrated case is that of W. Ross Ashby, a British neurologist who investigated the possibility of simulating brain activity [19]. In 1956, Ashby wrote a textbook entitled *An Introduction to Cybernetics*, [20] contributing to the diffusion of

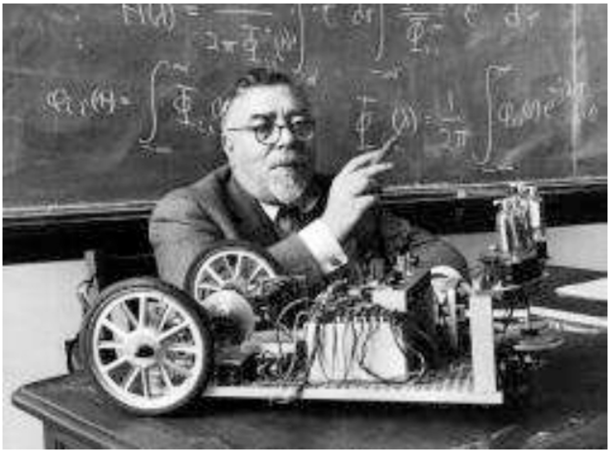

Figure 1. Norbert Wiener with Palomilla.

new ideas in Europe. We quote here a passage in Section 1 / 2, where he describes the peculiarities of cybernetics:

"Many a book has borne the title "Theory of Machines", but it usually contains information about mechanical things, about levers and cogs. Cybernetics, too, is a "theory of machines", but it treats, not things but ways of behaving. It does not ask "what is this thing?" but "what does it do?" Thus it is very interested in such a statement as "this variable is undergoing a simple harmonic oscillation", and is much less concerned with whether the variable is the position of a point on a wheel, or a potential in an electric circuit. It is thus essentially functional and behaviouristic. Cybernetics started by being closely associated in many ways with physics, but it depends in no essential way on the laws of physics or on the properties of matter. Cybernetics deals with all forms of behaviour in so far as they are regular, or determinate, or reproducible. The materiality is irrelevant, and so is the holding or not of the ordinary laws of physics."

Control

In the years of the rise of cybernetics, a parallel development involved the sister field of 'control'. The evolution of this discipline is treated in many contributions; see, for instance, [21, 22]. In

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this article, we focus on the activity promoted by one of the main associations in the field, the International Federation of Automatic Control (IFAC). In 1956, two important conferences on control were held, one in Milan (Italy) in April 1956, and one in Heidelberg (Germany) in September 1956, both with many attendees (over one thousand). This led to the founding of IFAC, an ad-hoc institution devoted to control science and engineering, the constitutive assembly of which was held in Paris on 11th September 1957. The first World Congress of IFAC was held in Moscow in the summer of 1960, three years after the launch of Sputnik, with some 2000 attendees. Wiener took part in this Congress of 1960, as described in [23].

After that Congress, many other IFAC World Congresses have been held once every three years in various cities around the world. The next one, the 22nd of the series, will be held in Yokohama (Japan).

Although very close to each other from a conceptual point of view, the two fields—cybernetics and control—have had quite diverging fates in the academy and society.

A keyword often mentioned by Wiener is *feedback*; as he wrote, the role of feedback both in engineering design and biology has come to be well-established. Feedback is also the main keyword for control science [24].

Although very close to each other from a conceptual point of view, the two fields—cybernetics and control—have had quite diverging fates in the academy and society. With the rise of information engineering, Cybernetics was progressively absorbed into the *mare magnum* of information and lost visibility. In [25], it is suggested to contemplate the possibility that the cybernetics moment was, in some ways, ahead of its time as the basic reason for its decline.

On the contrary, control had a solid impact in engineering schools with the establishment of ad hoc courses, whose success has been amplified in recent years, thanks to the development of fields such as robotics, process regulation, vehicle control, identification and data-driven methods.

Epilogue

The volcanic activity of Norbert Wiener marked the development of science and engineering in the past century. He could see clearly where others were just groping in the dark. Thanks to him, the notion of stochastic process entered engineering and became a tool for design. This was a kind of revolution since engineering had traditionally been a fully deterministic discipline. As Masani wrote as a tagline to his biography on Wiener: *"This book attempts to trace the interaction between mathematical genius and history that has led to the conception of a stochastic cosmos."*

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