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The Legacy of Norbert Wiener and the Birth of Cybernetics

Without intending to be an exhaustive historical account, this chapter provides some specific details regarding the concerns of the founders of what is now the science of systems or systemics, in order to understand the stakes that still remain extremely relevant today. Its objective is to avoid the anachronisms that are often the origins of serious misinterpretations.

In this chapter, we propose to revisit the key event system sciences, or systemics originated, in which the mathematician N. Wiener, professor at MIT, has been an emblematic actor[1]. The summary that we propose does not claim to provide a chronological history of the facts as far as it could be restituted[2], which would in any case not be of great interest. It attempts, on the other hand, to recreate the dramatic climate of the era in which all available researchers find themselves caught up in the efforts of the Anglo-American war to fight against totalitarian regimes. Some do so with conviction and without scruples, such as J. von Neumann, others due to a moral duty, such as N. Wiener who was a pacifist and felt disgusted by violence. This is a period of intense interactions and exchanges between exceptional scientific personalities, often of European origin, where urgent action against totalitarian regimes is the common good. To make sense of this situation, it is necessary to

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[1] But not the only actor! J. von Neumann played a major role, if not more important, on the practical and theoretical plans. For a complete overview, refer to G. Dyson, *Turing's Cathedral – The Origins of the Digital Universe*, Penguin, 2012; W. Aspray, *John von Neumann and the Origins of Modern Computing*, MIT Press, 1990, in particular Chapter 8, "A theory of information processing".

[2] One of the essential works that best describes this very particular atmosphere is the work by S.J. Heims, *John von Neumann and Norbert Wiener, From Mathematics to the Technologies of Life and Death*, MIT Press, 1980; and more recently, P. Kennedy, *Le grand tournant: pourquoi les alliés ont gagné la guerre, 1943–45*, Perrin, 2012.

imagine trying to put ourselves in the situation in order to judge the potential importance of the contributions made by each one, and to do this, it is essential to have a thorough understanding of the problem.

REMARK.– We have voluntarily ignored the contribution made by the biologist L. von Bertalanffy and his *General System Theory*, which today is only of historical interest[3]. Its influence in the field of engineering has been small, even zero, given the level of generality in which it was situated, and in any case, engineering was not his field of concern, contrary to N. Wiener, C. Shannon, J. von Neumann or A. Turing who "got their hands dirty" with machines and/or real systems.

1.1. The birth of systemics: the facts

The problem presented to N. Wiener[4] and his group at the MIT[5] was to study methods to increase the number of shots hitting the target and improve anti-aircraft defense, whose effectiveness could be measured by the ratio of the number of shots fired per downed airplane. Its overall objective was to improve the management of "shell" resources, inflict the greatest damage to the enemy (airplane pilots are a rare resource) and above all to save human lives.

At the time, when N. Wiener began his reflection, a summary of the technological environment would read as follows:

Gunners had perfect knowledge of ballistics and used firing charts to make adjustments to land-based cannons, for straight shots and for parabolic shots, over distances up to 20–30 km (correction required for the Coriolis force that is caused by the rotation of the Earth). The final targeting was carried out by observers close to the points of impact, who gave correction orders by telephone in 1914 and then by radio in 1939–1940. Shots were fired by the DCA (air defence) in a completely new environment onto moving targets – airplanes with speeds of up to 600 km/h, in other words, approximately 170 m/sec, at altitudes of 5–6,000 m. With shells of high initial speed, 800–1,000 m/sec, 5–6 seconds passed before the explosion capable of destroying the target was triggered, without taking into account the deceleration that slows down the initial speed.

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[3] For an exhaustive study, refer to the thesis by D. Pouvreau, *Une histoire de la "systémologie générale" de Ludwig Bertalanffy – Généalogie, genèse, actualisation et postérité d'un projet herméneutique*, EHESS, March 2013.

[4] Refer to Chapter 12, "The war years 1940–1945", from his autobiography, *I Am a Mathematician*, MIT Press, 1964.

[5] Among others J. Bigelow; refer to article "Behavior, purpose and teleology", cowritten by A. Rosenblueth, N. Wiener, J. Bigelow, which can be downloaded from the JSTOR website.

REMARK.– In 10 seconds of freefall, a weighted object travels approximately 500 m and reaches a speed of 100 m/sec (360 km/h).

Combined with the speed of the airplane and with the initiatives taken by the pilot who can change course, we can easily understand that the “shot hitting the target” is something highly improbable. It is also the reason why it is necessary to “spray” a very wide area, with many cannons and a great quantity of munitions, to have a hope of making an impact; it is best to forget about efficiency.

The first radar (radio detection and ranging) equipment made their first appearance in England where they played an essential role and allowed the RAF to contain the attacks by the Luftwaffe. The radar allowed regrouping bomber formations to be “seen” far in advance, something that no observer would be able to detect simply by visual means, given the distances, with *in situ* information an impossibility. Thanks to radar, the command center for aerial operations understands what is probably going to happen and can therefore position its retaliation in advance with maximum efficiency for “attack” airplanes. In other words, radar provides all information about the trajectory followed by the target: position, speed and possible acceleration, and integrates all that to calculate the probable trajectories of bombers.

MIT (Massachusetts Institute of Technology) had, at the time, one of the very first electronics laboratories for the study of servomechanisms – the Lincoln Laboratory. It later proved its worth in the construction of the SAGE system[6], the first anti-aircraft defense system that can be described as modern. Servomechanisms are becoming essential devices for automatic adjustment of mobile mechanical parts in such a way as to control their movements as minutely as possible and absorb the shocks that generate destructive vibrations. This is fundamental to move the chassis of anti-aircraft guns and follow the trajectory of target airplanes. Servo-control of the movement requires precise measurements, in particular of the mass to be moved, in order to activate effectors with the right adjustment data and make cyclic corrections.

These developing automatisms led to all studies concerned with the transfer functions that have the fundamental properties of reincorporating as inputs some of the results that they produce as outputs. Knowledge of the function of transfer, obtained either empirically by experimentation; theoretically by calculation, or by combination of both of these, is therefore fundamental data for correct control of the mechanisms in question.

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[6] *Semi Automatic Ground Environment*; refer to the book by K.C. Redmond, *From Whirlwind to MITRE: The R&D Story of The SAGE Air Defense Computer*, MIT Press.

Using these mechanisms, amplification will be possible in a ratio of 1:100, 1:1000 or much more, depending on the principle of the control stick or of the rudder. They use a low energy signal (electric current, shearing a hydraulic circuit) which at a smaller scale closely reproduces a phenomenon of much greater energy, such as the movement of a gun carriage that may weigh several hundreds of kilos, or even a few metric tons for the turrets of marine artillery for which compensation of the erratic movements of the boat must be made. Obtaining "true" signals that are uncontaminated by random "noises" from the environment is therefore absolutely essential.

We also know how to "calculate" some of the fundamental mathematical operations of differential and integral calculus, in a rapid and unexpected manner. This is by using analogical calculators that are quite difficult to manipulate, such as those that equip the gunsights of B29 bombers – another celebrated airplane among those used during World War II. The first computers arrived a few years later, but it is certain that N. Wiener already had relatively precise intuition given the exceptional environment that he was surrounded by and to which he was one of the star contributors. He knew J. von Neumann well and had held discussions with him on many occasions[7].

Rather than making long and fastidious calculations by hand, consulting tables and charts that are familiar to engineers, it was becoming simpler to carry out calculations directly with "programmed" functions in analogical form. And since in addition, we knew how to "clean" the signal that carried information about the background noise, it was possible to calculate the adjustment parameters required for the various appliances, on demand.

1.1.1. *The idea of integration*

N. Wiener's stroke of genius is to have understood that by integrating all these technologies appropriately and by managing to ensure all those working on their development worked together, we would be able to create machines capable of imitating behaviors such as the gesture of a baseball player. A popular sport among students at Ivy League universities on the East Coast, baseball requires precisely intercepting balls arriving with strange trajectories ("curveballs"), thrown by the "pitcher".

In a certain way, we can say that the machine has, in the memory of its electronic circuits, a "model" of the behavior of objects on which it is supposed to act, to be precise the airplane/pilot couple. The dedicated term to designate this type of

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[7] Refer to *John von Neumann: Selected letters*, History of mathematics, vol. 27, London Mathematical Society, American Mathematical Society, Miklos Rédei.

capacity, that only appeared with the first IT applications 30 years later, is "metamodel", because the rules that define it are independent of the medium. They are beyond, or above (the meaning of the Greek word *μετα*) the material format. Since programming is itself a model, the model of this programming is described as a metamodel to avoid confusion; it is a logical entity that is capable of instructing itself with its own rules, such as the universal Turing machine that can instruct itself or the grammar of written French which in this case is its own metalanguage. When computers began their exponential development, in the 1970s–1980s, we quickly understood that these fundamental rules to understand systems can, and even must, be specified in a language that is independent from the various possible targets. It can be expressed in the language of the universal Turing machine, independent of all technology[8], therefore adaptable to all physical formats that allow their logic to be expressed in a way that can be represented (analogue circuitry, electronic tubes and soon transistors). This is a pure abstraction, totally immaterial, but without which it is impossible to act. The model obtained in this way concentrates the information required for action of the system (what it does, in operational terms) and for action on the system (how it is done) in its physical reality; it defines the means of valid interactions, and to this end, it operates as a grammar of the actions to be carried out.

REMARK.– We note that any abstraction level in a system is a model of the entities that are thus abstracted. In a modern computer, there are easily 20 of them! Rather than piling up the "meta", it is more simple and clearer to say that layer N has a model of the layer that is immediately lower in the hierarchy of system entities, which allows us to program services on this same layer using only the interface defined by the model.

Now we turn to 1942–1943, when already one of the first laws of new systemics could be formulated:

To interact with an environment, any system must have an abstract model of this environment, meaning of the information, independently of the physical/organic nature of this environment and of the system (law no. 2 of the compendium, section C.2.2).

In the case of the firing system studied by N. Wiener, the model comprises rational mechanical equations, Lagrange/Hamilton version, applied to the ballistics of atmospheric trajectories whose parameters must be known: temperature, pressure, humidity, winds, etc.

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[8] In theoretical computer science, the Church–Turing thesis states that everything that is "calculable", in the logical sense of the word, can be expressed by a Turing machine which becomes, due to this, a universal modeling language; this is the case today where computer science has diffused into all disciplines.

Machines designed on these principles – imitating certain behaviors that are until then characteristic of living organisms – were thus attributed with an entirely mechanical "intelligence". Later, in the 1950s, it was known as "artificial intelligence"[9], completely constructed by human intelligence, thanks to knowledge of the laws of nature and the capacity for rapid and precise retroactions, for second- or third-order corrections (these are infinitesimal quantities), meaning the magnitude at instant t, its first and second derivatives. More prudent, Norbert Wiener used the term "machine learning", as early as 1946, less misleading and more precise than the media-friendly "artificial intelligence", to create dreams! A term that is still used in the United States, in preference to artificial intelligence.

In fact, the airplane trajectory is not random because it is subject to different types of determinisms that the pilot must take account of in their decisions, knowing that they can be impossible to predict, although probable. The airplane is subject to the laws of rational mechanics and to the laws that mechanics of its structures that can break, the strength of materials being one of the pillars of engineering sciences. The pilot can also execute dangerous, even mortal, maneuvers, for their own physiological safety ("black" sheet, increase of the apparent weight and difficulty in moving, loss of consciousness due to the centrifugal force, etc.), and it must take into account the decisions of other pilots in their squadron. Despite all these constraints, the trajectory can be extrapolated and calculated thanks to the data collected by radars. N. Wiener was a master of calculation of apparently random trajectories, such as those particles subject to Brownian motion, that he was the first to know how to calculate, using Lebesgue integrals of which this was one of the first concrete applications. He considered statistical mechanics, and its creators J.C. Maxwell, L. Boltzmann and J. Willard Gibbs, as an absolutely essential contribution to the new physics that was taking shape, and as a more correct understanding of the, operation of nature and of its representation.

REMARK.– Let us remember that for a curveball, at least four points are required. With a single point, we are in "a ball", two points determine a direction (the speed). With three we have the plane acceleration (curvature) and with four we have two planes and therefore the torsion of the curve – in other words a position and three vectors. With these four parameters, the movement can be located in a narrower and narrower cone.

This data can be the basis for calculation of the exact values, to provide to servomechanisms to point the guns in the right direction, follow the movement of airplanes and adjust the shell rockets so that they explode at the right moment, in the most probable region of the presence of airplanes. All of this takes place while

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[9] Term used by J. Mc Carty, in 1955–1957, then at Dartmouth, with a preference for the austere *Mathematical logic*.

correcting the margin with the latest data coming from the radars, as long as calculations are made fast enough and data is transfered without error[10]. Effectively, between the instant T of the situation, and the instant where the orders transmitted will be effective, there is a time difference ΔT; if ΔT is too big, given the evolution of the situation, the orders will not be adapted. This interval ΔT, response time and/or latency of phenomena, is a fundamental information regarding the transfer function.

N. Wiener very quickly understood that here he had at hand all the ingredients for a new method of analysis of the problems, allowing new solutions to situations that had remained inaccessible to analysis because they were too complex – far beyond "simple" machines that engineers had dealt with until then. And with a correct interaction of what is "simple", we could create something "complex" that is controlled, useful and organized, which respects the laws of engineering. His own way of creating order in a world that is subject to undifferentiated disorder.

He christened this "new science" *cybernetics*, or the art of steering, in the same way as a helmsman, by adapting the Greek word (κυβερνητική) used to designate the pilot of ships with which the ancient Greeks had conquered the Mediterranean – an unstable sea if ever there was one – and a term that is found in the roots of many words such as government, to govern, etc.

The very essence of this new science pertains to time-related actions that are carried out in an unstable environment – to go from a point A to a point B in a nonlinear fashion, exactly like a helmsman who knows that a straight line is never the right way to go about setting a course when currents, tides, winds, the movement of the boat (rolling, pitch, yaw), waves, etc. need to be taken into account to maneuver the sails and the rudder. The actions carried out are finalized[11], meaning organized and controlled as a function of the objective to be reached, the goal, and this is the new fundamental point, which is a moving target resulting from an environment that is itself structured but whose laws are largely unknown, although they do exist (much later, deterministic chaos was used to characterize them). It must therefore be possible to continuously adapt the action plan, which is difficult with analog calculators, but which is intrinsic to the architecture of von Neumann where the information recorded in the computer memory (computing instrument in his terminology) is sometimes

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[10] In his book dated 1951, *Reliable Organisms From Unreliable Components*, von Neumann wrote: "Error is viewed, therefore, not as an extraneous and misdirected or misdirecting accident, but as an essential part of the process." Also refer to Chapter 15, "Theory of self-reproducing automata", in the book by G. Dyson, *Turing's Cathedral*, already cited, which is essential regarding the central role played by the errors in the engineering process.

[11] Before the very official Macy Conferences, from 1942 to 1953, there had been an ephemeral Teleological Society which met informally; refer to S.J. Heims, *The Cybernetics Group*, MIT Press. In French, refer to the book by J.-P. Dupuy, *Aux origines des sciences cognitives*, which gives a good overview of this, but from a point of view that is subject to discussion, interesting in the same way as everything else he has done and written.

program and sometimes data (but another 10 years were required before this logic dream became reality). How can the environment be put to good use to reach the objectives: this is the ambition of cybernetics. To do this, it will be necessary to be “intelligent”, in N. Wiener’s meaning of the term, meaning as a mathematician[12].

Taking time to think about it, we see that we are dealing with a double trajectory[13], a double dynamic. On the one hand, the aspect imposed by the environment (meaning what is considered as not part of the system), what biologists like C. Waddington named “epigenetic landscape” (that René Thom rechristened substrate space or even phenomenological deployment) and on the other hand, the mobile aspect that the pilot can direct taking into account the intrinsic properties of this mobility and the experience that it has of the behaviors observed in the environment and of the evolving dynamic that characterizes it. The steering therefore consists of servo-controlling the trajectory to go from A to B, using the environmental dynamics to advantage in order to optimize the journey. When the pilot has navigated sufficiently and acquired experience – either empirically or theoretically through knowledge of the phenomenological laws that structure transformations of the environment that they are also part of – they know how to put the actions together that will allow them to reach their goal, scheduling that they alone can judge because they know the local situation.

The pilot must therefore extract information from their environment and to do this, they must have suitable sensors, and translate this information in the behavioral “language” of the effectors of the mobile that the designer is master of, an operation that physicists and electronic engineers are very familiar with, for which the dedicated term is “transduction”, for example transform an electric current into hydraulic pressure servo-controlled on the signal conveyed by the current (see Chapter 6).

In N. Wiener’s approach, anyone who uses the term interactions, implicitly means elements that interact in a certain order via energy exchanges. These elements are the constituents of the system (the buildings blocks in today’s computer science jargon; a much better term than that of “black box” often used at the time), to the exclusion of others that are therefore simply ignored, but which exist all the same.

For N elements, there are $N \times (N\text{-}1)$ monodirectional exchange links, but if the system organizes itself, if certain elements have a “memory” (possibly from layered human operators), it will be necessary to consider all the parts of these elements. Either through theoretically 2^N combinations or sequences of temporal actions that are possible in an even greater number, sequences that will be investigated thanks to

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[12] Refer to his autobiography, *I Am a Mathematician*, MIT Press, 1956, which leaves no doubt about the way we see the world.

[13] In geometry, these are graphs known as tracers; refer to https://en.wikipedia.org/wiki/Tractrix.

the theory of automatons for which J. von Neumann provided the basis at a later date[14]. The beginnings of the theory or theories of complexity therefore took root right at the start of the science of systems, but it was J. von Neumann who was the true initiator[15]. Curiously, N. Wiener never talks about this, nor does he talk about the theory of automatons, which does not mean that he did not know it[16]! Organizing this complexity, meaning specifying the architecture of the system using rigorous and precise logicomathematical models, quickly became the organizing center of projects, such as the SAGE system, with J. Forrester who carried out the first living demonstration of this in the 1950s.

He was the first to become fully aware of the practical problems of interdisciplinarity and attempted to resolve them, thanks to models that allow exchanges between the concerned parties, including military personnel in the case of SAGE[17].

Concerning the very object of cybernetics, N. Wiener's point of view cannot be clearer. He tells us[18]:

> "From the point of view of cybernetics, the world is an organism, neither so tightly joined that it cannot be changed in some aspects without losing all of its identity in all aspects nor so loosely jointed that any one thing can happen as readily as any other thing. It is a world which lacks both the rigidity of the Newtonian model of physics and the detail-less flexibility of a state of maximum entropy or heat death, in which nothing really new can happen. It is a world of Process, neither one of a final equilibrium to which Process leads nor one determined in advance of all happenings, by a pre-established harmony such as that of Leibniz… Life is the continual interplay between the individual and his environment, rather than a way of existing under the form of eternity."

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[14] Concerning this very fundamental subject, we can re-read the memo written by C. Shannon, *Von Neumann's Contributions to Automata Theory* (readily available on the Internet); also refer to the recent book by G. Dyson, *Turing's Cathedral – The Origins of the Digital Universe*, already cited.

[15] Refer to the retranscriptions of his conferences at the Hixon symposium, September 1948, on *Theory of Self-reproducing Automata*, University of Illinois Press, 1966, published posthumously by A.W. Burks; and volume V of the complete works: *Design of Computers, Theory of Automata and Numerical Analysis*, Pergamon Press, 1961. This is irrevocable for anyone who wants to take the trouble to read, then. S. Ulam developed certain ideas provided by his colleague and friend about self-reproducing automatons.

[16] He certainly uses the term "automaton", but not in the rigorous mathematical sense that von Neumann gave it in his various writings.

[17] On all these aspects, refer to K. Redmond, T. Smith, *From Whirlwind to MITRE, The R&D story of the SAGE Air Defense computer*, MIT Press, 2000, already cited.

[18] *Autobiographie*, p. 327.

This is indeed about the science of systems, with no doubt, even though we could detail his words further.

1.1.2. *Implementation and the first applications*

Cybernetics has had a strange fate on each side of the Atlantic.

In the United States, it has remained *grosso modo* an engineering science where it has prospered under the auspices of the MIT, with in particular J. Forrester, SAGE project director and future professor at the Sloan School. He published, among others, two books that marked important milestones in systems sciences: *Industrial Dynamics*, in 1961 and *Principles of Systems*, in 1971, recently republished by Pegasus Communications. *Cybernetics* by N. Wiener, (Forrester version), has been successfully included in the engineering cycles of complex systems, sometimes without even being mentioned by name, a true implementation of the "wou wei", the art of governing without action, without effort and spontaneously, of the emperors of China[19], particularly in engineering of quality[20] which is fundamentally an integrated control throughout the system lifecycle in compliance with the service contract requested by the system users. Quality is a "trajectory", a pathway, which is constructed by taking into account the hazards of the project environment, including those of organizations. For this, it must be kept in mind by all the actors and concerned parties, and not in a quality sense that is exhibited like a dancer to demonstrate that it is being done. The vocation of quality is to be, not to only seem, prominent and not salient, which acts like a force field. The entropic nature of human activity means that if it is not maintained over time, it degenerates and the undifferentiated disorder takes over again.

Recently, systemics has even undergone a true media success in the United States with a cult book, *The Fifth Discipline*, which presents *System Thinking* for a wide-ranging public, in the simple language that English-speakers enjoy so much[21].

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[19] In the Forbidden City in Beijing, in the meeting room of the Palace of Tranquil Longevity, all visitors can see the two characters "wou wei" written in traditional Chinese above the throne of the Emperor: 無 爲.

[20] Refer to the works of G. Weinberg, in particular *Quality Software Management, System Thinking*, Dorset House Publishing, 1991.

[21] *The Fifth Discipline: The Art and Practice of the Learning Organization* (first edition 1990, latest edition 2006); book by Peter Senge, professor at MIT. P. Senge explains in this book the integrator role of *System Thinking* in what is known as *Core Disciplines*: *Personal mastery*, *Mental Models*, *Building Shared Vision*, *Team Learning* which are also great classics in the field of quality management and project management.

In France, things have been different because very quickly cybernetics sought fields of application that went far beyond what they were capable of explaining, owing to a lack of prediction, in sociology of organizations or in biology[22]. Norbert Wiener himself probably contributed indirectly to this state of affairs under the influence of his book destined for the wider public *The Human Use of Human Beings*, which was very quickly released in French under the simple title *Cybernétique et société*[23] (meaning "Cybernetics and Society"). This a more accessible book than his *Cybernetics*: *or Control and Communication in the Animal and the Machine*, which appeared simultaneously in 1948 from MIT Press and Hermann in France. In the rest of this volume, we will denote that book by the shorthand C/CCAM.

Unavailable for a long time in French, this seminal book was translated by Éditions du Seuil, in 2014, in the *Sources du savoir* collection, with a presentation of the context by the science historian Ronan Le Roux, based on his PhD thesis work, *La cybernétique en France (1948–1970)* (cybernetics in France), defended in 2010[24]. The French title is: *La cybernétique – information et régulation dans le vivant et la machine* (meaning: Cybernetics – Information and regulation in living beings and machines). We note that *control* has been rendered by control, which is perfectly correct, but that *communication* and *animal* have respectively been rendered by information and living, two translations that we can contest. As Wiener himself says, "Traduttore, traditore" (C/CCAM, Chapter VIII, "Information, language, and society").

In the introduction to their book *The Mathematical Theory of Communication*, Shannon and Weaver are, however, particularly clear. They tell us, in the introduction: "The fundamental problem of communication is the reproduction, either exactly or approximately at one point, of a message that was selected at another point. Frequently the messages have *meaning*; […] These semantic aspects of communication are irrelevant to the engineering problem." In communication, we are only interested in the structure, in the syntax and the coding, and of course in the mistakes. The distinction between communication and information is therefore very radical. When we talk about ICT, we note the same distinction; in academic disciplinary fields, we distinguish sciences and technologies of information and communication (STIC) from other fields, while maintaining the distinction between information and communication. Mathematics, in the sense that it constitutes the "language of nature", is part of the STIC, but mathematicians would certainly be offended if we said to them that their science came from cybernetics, *irrelevant* they would say! Look at the short text by Grothendieck, found below. This choice of translation is therefore not the most judicious, at the least, because it maintains a confusion, which means that the proposed translation is at the limit of a false meaning. "Information" is much wider than "communication", and includes sciences of language, natural and/or artificial, including

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[22] We can re-read the remarkable recension of this work produced by L. de Broglie in no. 7 of the NRF review, July 1953, *Sens philosophique et portée pratique de la cybernétique*, unfortunately too quickly forgotten.

[23] Several editions, including the most comprehensive by UGE/10-18 in 1971.

[24] Available from Garnier under the title *Une histoire de la cybernétique en France*, 2018.

mathematics. The information is intentional by nature, performative as linguists say, because it conveys meaning, which is something that the communication according to Shannon refuses to do, and which, just like the laws of physics, needs to remain objective. The same can be said for the term “living”. Animals are unequivocally elements of the living, in general; with viruses, the frontier with chemistry is perhaps more blurred? Animals are living organisms that are born and die; their main objective is to survive, because as P. Kourilsky states in his book *Le jeu du hasard et de la complexité*, “to live, you firstly need to survive”. To survive, eat, reproduce, animals have projects, they develop strategies, with intermediate objectives, and a final goal. Where there is no purpose, there is no control, because in order to control it is necessary to know with respect to what we are controlling; this is perfectly clear in C/CCAM, as well as in the article “Behavior, purpose and teleology”, previously cited. Why has this choice of translation been made? Is it the very notion of teleology that bothers translators of the book? We know that the “politically incorrect” term purpose/teleology is banned from biological speech, let us say since the book by Jacques Monod, *Le hasard et la nécessité (Chance and Necessity)*, replaced by “chance” which in this case does things very well. This is a little strange in engineering sciences, because what is more teleological than engineering? Even though we use the term “project” because it is indeed teleology that we are talking about. The entire quality approach, up to the most recent developments, like lean management, is teleological in its very essence. Project management is a perfect example of application of cybernetics to an engineering organization as is practiced in systems engineering. Norbert Wiener was a professor in one of the most prestigious engineering institutions and he trained engineers (see section 1.3). Manufacturing machines or systems presumes that there is an objective to be reached, an objective that will materialize in a construction plan, with the detail of the parts and of the assembly method, without which integration is impossible when the number of parts exceeds a few dozen. With 100 parts, there is a factor 100 (noted 100!) combinations, in other words approximately $\cong 9.3 \times 10^{157}$; given that there are only 10^{80} atoms of hydrogen in the observable universe, do we understand that without a plan, chance will not operate?! In an engineering project, the importance attributed to chance must be zero; this is what we call risk management, a risk that must be compensated for by suitable counter-measures for the engineering to be sound.

I have not gone through the entire translation with a fine comb, but we can all the same remark that in the introduction to the 1948 version, the article by Rosenblueth, Wiener and Bigelow, above, appears as a footnote, whereas the note disappears in the translation (done on the 2nd edition in 1961 with MIT Press, whom I have not consulted). To be perfectly honest, R. Le Roux does mention this article in his presentation, and gives a brief summary of it.

These few reservations aside, we acknowledge this translation; but as always, it is necessary to consult the sources themselves, which nothing can replace.

Box 1.1. *The translation of* Cybernetics *by N. Wiener*

Thanks to cybernetics, N. Wiener intended to explain the complexity of human societies, history, which in positivistic minds like A. Comte awakened old memories of the social "engineering" and "physics" of which É. Durkheim positioned himself as a master in his founding works. In the atmosphere of the 1950s, in the middle of the Cold War that may have turned hot at any moment, some dreamed of "machines to govern the world" managed by "scientists", considered more reliable than the politicians and ideologists that had plunged the world into chaos. Utopic dream, of course, because since von Neumann had restated, a short time before his death by interrogating: "Who is guarding the guardians?" This is the entire problem, centralized and/or distributed, you must choose, and interact, avoiding both gulags and re-education camps for "new humanity", and the individualistic disorders of "every man for himself".

It is still the case that cybernetics never really entered the territory of engineering sciences, except at the edges, thanks to individual initiatives[25], with a small exception in the CNAM syllabus, where the action of professors J. Lesourne[26] and J.-P. Meinadier[27] must be shown; in any case not in the large engineering school programs, where it had a reputation as rather scandalous and not serious. It is true that when we examine the jargon introduced by Edgar Morin in a cold light and without searching for controversy, we have a sickening feeling due to the excessive inflation of verbs and the combination of hollow words that flow freely[28]. "Nebulous" our teachers would have said! Creating neologisms each time that we believe we have discovered something original has never explained anything, nor resolved the smallest problem. We have known this ever since G. d'Ockham and his principle of sobriety, at least!

Without injury to the past, and reconstructing a plausible situation, perhaps in the mindset of N. Wiener, this was a way of providing retort to J. von Neumann who had just released his very famous *Theory of Games and Economic Behavior* that was going to revolutionize economic sciences – except that he did not have the mathematical language that would have allowed him to express his ideas that were forming in all directions. For anyone who has read in detail his latest works, in particular *God & Golem, Inc.* published in 1964, the year of his death, it is very

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[25] Such as the one by G. Donnadieu at the IAE; refer to his book, written with M. Karski, *La systémique*, *Penser et agir dans la complexité*, 2002.

[26] His book, *Les systèmes du destin*, Dalloz, 1976, and a few others, have been a basis for his lessons in forecasting.

[27] His two books, *Ingénierie et intégration des systèmes*, 1998, and *Le métier d'intégration de systèmes*, 2002, both with Hermès, remain essential reference works.

[28] This remark only relates to the part of his book that concerns *La méthode* and similar texts; his sociology analyses are generally interesting. Refer to the point of view expressed by J.-P. Dupuy in *Ordres et désordres*, Chapter 7, "*La simplicité de la complexité*", that I share.

clear. He said to us (p. 88): “cybernetics is nothing if not mathematical”, and a little further: “I have found mathematical sociology and mathematical economics or econometrics suffering under a misapprehension of what the proper use of mathematics is in social sciences and of what is to be expected from mathematical techniques, and I have deliberately refrained from giving advice that, as I was convinced, would of course lead to a flood of superficial and ill-considered work.”

In addition, he was quite critical of J. von Neumann’s game theory because he considered that it was impossible to assimilate the economy to an immobile game, in a world where everything changes, including the rules of the game, which is obvious; unfortunately, J. von Neumann, who died in 1957, was no longer there to provide an answer. No doubt that N. Wiener would have had a strong reaction to jargon and the conceptual clutter that inundated *his* theory, and made cybernetics inoperable, at least for engineers, – he who had been a professor at one of the most prestigious universities in the world, his beloved MIT. Concerning “financial mathematics”, an oxymoron, and the “systemic crisis” that we have been going through since 2008, he would very probably choke with anger “Ill-considered work!”

Now this language that is required for a good description of the processes that are at work in systems, came about in the 1950s–1960s. Today we are well aware of this: this is the language of computer science, and more particularly languages such as IDEF, UML/SysML and BPML/BPMN[29].

R. Thom who was very strongly opposed in his typically undiplomatic fashion to the “dictatorship of fuzzy concepts”[30] had attempted to answer this with his catastrophe theory, a name introduced by his English colleague C. Zeeman. He did not claim to have instigated himself, but even this was not a great success, for the totally opposite reason that a high level of mathematics was required to understand his geometric language, involving differential manifolds and singularities. One of his best commentators, the great Russian mathematician V. Arnold[31], said that between two lines of Thom, 99 more lines were needed to create something that was at least comprehensible! His work *Stabilité structurelle et morphogenèse* (1972) could therefore have rivalled the thousands of pages of the seminar on algebraic geometry given by his colleague at the IHES, A. Grothendieck. Communication was decidedly difficult!

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[29] Refer to https://en.wikipedia.org/wiki/IDEF; https://en.wikipedia.org/wiki/Systems_Modeling_Language; in addition to https://en.wikipedia.org/wiki/Business_Process_Modeling_Language.

[30] Refer to his article published in *Les Débats*, “*Halte au hasard, silence au bruit*”, 1980.

[31] Refer to his book *Catastrophe Theory*, 3rd edition, Springer, 1992.

This was therefore another lost opportunity and yet the requirement had been created by the significant increase in the complexity of the systems designed by engineers, with computer science endlessly replicated or almost so, at all levels as had become obvious in the Apollo space projects and especially the *Space Shuttle*. Complexity of systems whose risks are beginning to be recognized, if not truly understood, such as "high-frequency" transactions, but can we still talk about engineering in the context of financial computer science[32]? Risks that also understandably give rise to irrational fears. The obligation to provide explanations is therefore more pressing than it has ever been in the history of sciences and techniques. For someone who does not understand, knowledge very easily turns into magic, which would open the door to irrational ideas, were they not saddled with mathematics that lack in rigor, such as in finance.

Having a general method for consideration of the complexity of the system of the world in the 21st Century and extracting from this all that can reasonably be automated (without losing grip on the pedals and remaining in control of events) is the essence of the problem that we need to resolve.

To do this, we must consider three areas of complexity, in a symbiotic relationship, at the very center of systems in interactions, distinct but indissociable.

The complexity of the technical objects/systems[33] that we are capable of constructing and maintaining is the traditional complexity that engineers have always had to overcome, ever since the era of cathedrals.

This basic complexity has been added to by:

– the complexity of corresponding engineering projects that force all the interested parties in the system to work in a coordinated manner, that is, in the case of a large project, several thousands of actors are required to work in phase with each other over the long term (in quantum mechanics, we would say they are "correlated");

– the complexity of uses – meaning semantics, the "what is this used for" – induced by technical objects that we have available and the new requirements that these objects provoke, objects that are now accessible to all; with Internet and the World Wide Web, we are talking about millions of users, even billions!

Organizing and integrating these three complexities (see Figure 1.2) into a coherent whole, finding the right compromise, or at the very least one that is

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[32] Refer to the book by J.-F. Gayraud, *Le Nouveau Capitalisme Criminel*, Odile Jacob, 2014.

[33] Concerning this double notion, refer to G. Simondon, *Du mode d'existence des objets techniques*, Aubier, and B. Gille, *Histoire des techniques*, Encyclopédie Pléiade.

acceptable, without taking inconsiderate risks, this is the challenge that will be examined in Chapters 8 and 9. One of the most significant characteristics of complexity[34] is the emergence of properties and/or new behaviors that it is impossible to anticipate, in particular everything that relates to uncertainties of all kinds that are present everywhere, which in information theory is known as “noise”. Learning to compensate for these hazards, to live intelligently with “noise”, or even to use it in the same way as in error correction codes, is the key to complex systems engineering.

We can summarize the sequence that began in the 1940s by the representation in Figure 1.1. This is the result of the work of two generations of engineers and researchers. The third, which is beginning to position itself at the controls, has immense prospects ahead, if it is able to rise to the challenge and demonstrate that it is up to the task.

In this sequence, France has proved itself worthy, with systems such as STRIDA or SENIT created by the Ministry of Defense. It has a data transmission network that is among the best in the world, thanks to its historical operator, France Télécom and its historical research center, the CNET (which is now FT R&D or what remains of it). Thanks to EDF’s energy transport network, (which is now EDF/RTE), all French households and companies have a high-quality, low-cost supply, a system that has shown many times how robust it is, and that we will come back to in section 8.2. We could mention aeronautics, the space industry, the automotive industry, information systems with the MERISE method that introduced on a large scale the logical concept of computer science metamodels, etc.

All this demonstrates, over and above all the more or less pessimistic speeches, a great capacity to manage highly complex environments that are one of the legacies of the generation of the 30-year post-war boom in France, and that we need to make productive and improve.

The diagram in Figure 1.1 is a simplification, but it demonstrates a dynamism and a stage of advancement that cannot be ignored. In the 1970s–1980s there was a profusion of projects that did not all produce the expected results but which obviously demonstrate a capacity that will be useful. For this, students at reputable scientific universities and business/management schools must reinvest in the scope of systems and industry, abandoned in the 1990s–2000s, as the various reports on competitiveness have widely demonstrated.

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[34] Refer to the book by the physicist P. Bak, *How Nature Works – The Science of Self-Organized Criticality*, Springer, 1996.

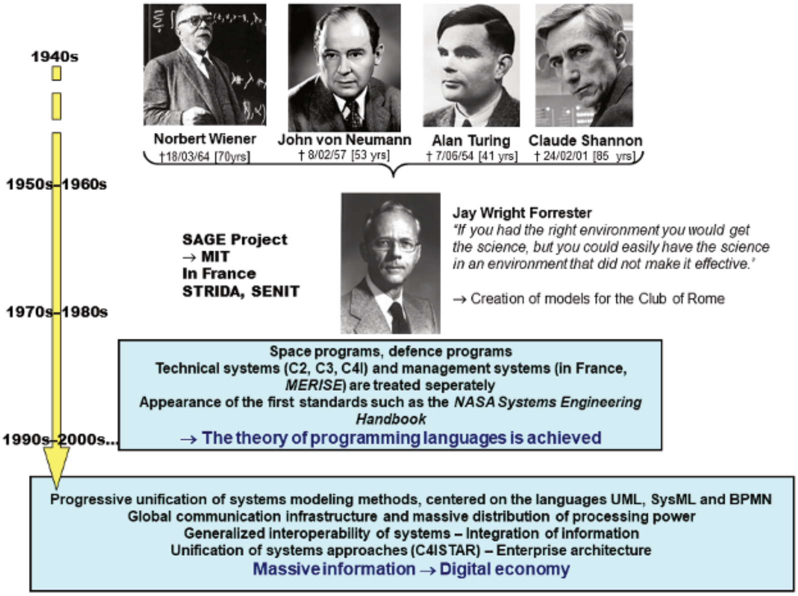

Figure 1.1. *From the generation of pioneers to the digital economy generation*

It is certain that the system culture that today culminates in C4ISTAR (*Command, Control, Communications, Computers, Intelligence, Surveillance, Target Acquisition and Reconnaissance*) systems, this fifth discipline to reuse the title of the American best-seller by P. Senge, a professor at the MIT who is very familiar with the works of J. Forrester, played a critical role.

REMARK.– It is not prohibited to believe that the general culture (both scientific and managerial) of French engineers familiar with abstraction including with its humanist dimension, has a lot to say on the subject, given our accomplishments and our expertise, such as the electronuclear program implemented by EDF which allows each one of us to have cheap and high-quality energy.

1.2. Modeling for understanding: the computer science singularity

In the 1990s–2000s, it became obvious that what the pioneers N. Wiener, J. von Neumann and A. Turing had imagined was beginning to turn into reality. Of the three, only N. Wiener perhaps knew about transistors (he never talked about them). None of them could have foreseen that one day, thanks to the magic of microelectronics and the integration of components, machines would be available (von Neumann referred to a computing instrument) with performance a million times better than those that they had contributed to creating, and means of communication allowing: (a) images to be transmitted in real time from one end of the planet to the other, and (b) machines to work in networks on problems of a size that goes far beyond what any human would be capable of mastering. This capacity was going to allow an "en masse" programming, *in the large* as our American colleagues say, that was almost inexistent in the 1950s. However, some 40 years later were processed billions of lines of code programmed by millions of programmers making up the profession today. Each second, hundreds of billions of programmed instructions loyally execute, without error nor fatigue, what the programmers recorded in the memory of the machines, measured in billions of characters. But as we will see in this book, as an echo of a strange symmetry this immense success generated simultaneously its set of new problems, in particular safety.

An instrument like the LHC[35] at the CERN produces billions of pieces of information for each experiment, that only correctly programmed computers are capable of analyzing and "understanding". What the wider public knows as *Big Data* is only accessible thanks to the programs aiding mathematical processing of information, only able to identify in the apparently shapeless "mass" what carries interesting information.

Today, at the start of the 21st Century, several billion people, via their smartphones and/or the tablets, have a capacity for interaction and access to information via the Internet and the World Wide Web, at a scale that has never been seen in the known history of humanity. They can form communities of interest via social networks, capable of mobilizing themselves almost instantaneously for a cause and to give feedback in real time or nearly so. No need to be a prophet to understand that all our modes of governance, that the "authority" and education, that the constitution of our common good, our consumer habits, etc., are going to be profoundly changed, for the better or for the worse. Our terrestrial or aerial vehicles integrate dozens of microprocessors and carry onboard millions of lines of code, directly and indirectly, to ensure our security and optimize the resources. Originally descriptive and qualitative, modeling has become quantitative and massively calculatory, a precious aid to the non-trivial exploration of complex situations in which the space of the states generated by the combinatory is immense (for a memory of 1 GB this gives the colossal number 256^{10^9}). A universal usage that reinforces the veracity of the Church–Turing thesis.

REMARK.– We are faced with what mathematicians call singularity, a bifurcation, and what physicists call a change of phase – a restructuration of material or even a metamorphosis, but from which we do not know if a bee or a hornet will emerge. We are on the edge of a watershed where, once we cross over, nothing will be as it

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[35] Refer to the book *The Large Hadron Collider: a Marvel of Technology*, EPFL Press, 2009.

was, where a new passage will appear and take shape, where the transformation is very quickly going to become irreversible, taking into account the colossal energies that are at stake and carried by the 9–10 billion inhabitants that will soon be present on earth.

Today, we have all the technology to provide good systemics. We have above all the right concepts and the right languages, such as those of abstract machines that we know how to define with all the rigor and precision required by the problem that needs to be resolved, which can lead to the creation of DSL/Domain Specific Languages. We can interact and give feedback in a certain manner at a scale that Norbert Wiener would never have imagined, with an MIT that has significantly developed its leadership[36]. Individuals and community interests have become "active units" for the first time in social history[37] to borrow a good expression used by the economist F. Perroux. Intelligence – meaning our capacity for adaptation to the environment – can be distributed and controlled by exchanges of information, and in doing so defuse conflicts thanks to models such as game theory that J. von Neumann opened the door to, in particular those that model cooperation. Without cooperation, without feedback, there is no solution to the conflicts that are unavoidably going to appear.

Models of game theory perhaps avoided a transformation of the Cold War into a global disaster, but we will never be certain of this[38]. However, what we can be sure of is that they have added a little rationality where ideologies/ideologists had cast doubts on the capacities of mankind to surpass fratricidal rivalries. Models such as the "prisoner's dilemma" would perhaps have removed N. Wiener's doubts about game theory[39].

Programming, in other words in fact modeling and calculating, has become a new way of reasoning, which it has taken us several decades to understand correctly after Alan Turing and a few others had laid down the foundations[40]. We can imagine machines keeping pace with humans, but what gives the logical capacity to the machine is its programming which itself remains dependent on human intelligence and under control of programmers. Deep Blue did not convince Kasparov, but rather it was the programmers who programmed the IBM machine. This is something that must never be forgotten. Learning programming, in a broad sense and for this

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[36] Refer to the website www.cesames.net of the authors for more information.

[37] F. Perroux, *Unités actives et mathématiques nouvelles*, Dunod, 1975.

[38] Refer to the book *The Strategy of Conflict*, reprinted in 1981, by the 2005 Nobel prizewinner, T. Schelling.

[39] Refer to R. Axelrod, *The Evolution of Cooperation*, 1984, available in French from Odile Jacob, *Donnant Donnant*, 1992 and M. Nowak, *Super Cooperators – Why Cooperation, Not Competition, is the Key to Life*, Canongate Books Ltd., 2011.

[40] Refer to G. Dowek, *Métamorphoses du calcul*, Le Pommier, 2007.

reason, must be at the heart of training of future citizens of society known as "digital", in the same way as reading and multiplication tables, after the invention of the printing press. Our future and the condition of our freedom are contained herein. The act of programming, its "performative" aspect as linguists say, is at the heart of the system approach.

We therefore have technology to create good systemics, but we are also in particular going to have to do this by necessity to organize the complexity of the world in the 21st Century, to put order, a minimum of rationality and good sense, in what could also become a gigantic chaos of information, this time at the scale of the planet. It is necessary to be blind and deaf to imagine that the current socioeconomic disorders are able to continue for a long time "business as usual", and then there will be a deluge. Systems science teaches us that, sooner or later, any imbalance that violates the structural invariants of the system leads to a correction in proportion to the amplitude of the imbalance taking into account the energies at stake; the shock in return, like a "tsunami", can be violent if it is neither anticipated nor controlled. The warning signs are always second-order weak signals[41], undetectable by statistical surveys. Without the theoretical model by Brout, Engler, Higgs *et al.*, the experimental physicists at the CERN would never have been able to discover the Higgs boson. Here is what we need to convince ourselves of. It is not sufficient to have a lamp or a map, it is still necessary to know where to look, which will determine how. This is why we have the moral obligation to obtain the consent of the wider public. What we need is a grammar to understand the world in which we are now one of the interested parties, both subject and object, spectator and actor – a grammar whose language, in other words our programs, is computer science language that it is now essential to master. In addition, systemics can largely help us to see a little more clearly. With the current state of technology and engineering methods, there is no alternative.

1.3. Engineering in the 21st Century

In the engineering problems that are created by modern, globalized and now massively computerized societies, a distinction needs to be made between the necessary, which remains stable, and the contingent that can fluctuate as a function of the environment and of external constraints (see PESTEL, section 8.3.3). Delivering technology that will in the end be rejected by users for whatever reasons, or that it will turn out to be impossible to maintain in the long term, or dangerous, must from now on be considered an inexcusable mistake because it is potentially fatal. Phenomena caused by ageing of elements, by definition unknown, must be able to be observed, unless they are understood. It is therefore necessary to think

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[41] Refer to the case of the electric system.

about them right from the start of the system lifecycle, when the requirements are expressed, and in the architecture phases, by associating all the interested parties. For this, the system must be instrumented in such a way that it can be observed from inside, taking its invariants into account.

The complexity that this new engineering must organize, emerged progressively from work produced in the 1980s–1990s. It is three-fold, as indicated in Figure 1.2.

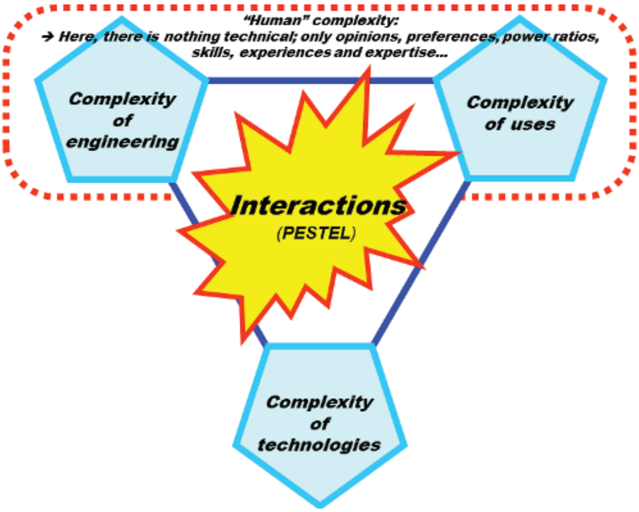

Figure 1.2. *The three complexities of new engineering*

Besides the complexity of technologies that has continued to develop incessantly, for this it is sufficient to look at a latest generation microprocessor, with its billions of components, or an assembly chain of robots with its hundreds of machines in the automotive industry, two other complexities described as "human" in the diagram have added themselves: one concerning engineering and its processes under development, and one concerning the uses – meaning the semantic – made by users that are no longer engineers like in the first systems, hence uncertainties and human errors. For the complexity of technologies, we have available a wide range of modeling and simulation tools that have undergone an almost exponential development thanks to our scientific expertise, of which some is old, but above all thanks to the formidable development of information and communication technologies (ICT). This has no precedent in the history of techniques. The duration of the design period of a modern airplane like the A380, or the Boeing Streamliner, has thus been divided by two thanks to the "virtual" design offices set up by aircraft manufacturers, which is from 10 years to less than 5 years!

Human complexity is of an entirely different order. Human rationality is "limited" to paraphrase the title of a book by H. Simon[42], and deviant behaviors must not be excluded, as underlined in the studies that have been carried out following the *Challenger*[43] space shuttle disaster, without mentioning the misguided ways of finance that have made the financial system work for the richest 1%[44].

The error is human, as we often say, but it is also all-pervasive in nature. What we need to find are rules of engineering and architecture that compensate for them, as J. von Neumann had anticipated in his studies about reliable automatons. The systems under development that we have dedicated several books to are fundamentally human systems, even though they are now relatively computerized. Engineering of the interface between users and systems, now based on a graphical screen, has become a major theme of systemics.

These three sources of complexity interact with each other, thus creating new combinations that need to be taken into account, taking them two by two, then three by three, with a total of seven possibilities. The corresponding interactions can be organized with the help of PESTEL[45] factors (political, economic, technological, ecological, legal; see Chapter 8) that we will come back to. Ignoring these factors, allowing the complexity to stay in metastasis is equivalent to a death stop for the system whose development cycle will not pan out to its usual term.

Hence, the analysis method proposed in this book, which is intended to be a general method of a framework for engineering systems of systems, must allow us to:

– discover what must necessarily be included, and to imperatively identify the hard core of the system, its irreducible complexity, that will be its organizing center and its spinal column; this vital information is the model of the system, its "map" to reuse the famous expression, often misunderstood, by A. Korzybski: "The map is

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[42] Refer to *Models of Bounded Rationality*, vol. 3, MIT Press; also refer to D. Kahneman, A. Tversky, *Choices, Values and Frames*, Cambridge UP; or even G. Allison, the famous *Essence of Decision*, 1999.

[43] Refer to D. Vaughan, *The Challenger Launch Decision*, Chicago UP; or even the series of books by C. Morel, *Les décisions absurdes*.

[44] Thesis defended by the Nobel prize winner J. Stiglitz in his book, *Le prix de l'inégalité*, 2012; also refer to the works of G. Giraud, for example *Illusion financière*, 2012.

[45] Refer to https://en.wikipedia.org/wiki/PEST_analysis.

not the territory”[46]. This is a metaphor that tells us that reality must never be reduced to a model, as sophisticated as it may be;

– express and communicate what has been understood to all concerned parties in order to obtain the agreement of each of the actors in language that they understand, according to their point of view, therefore a plurality of models whose coherence must be managed, which is the subject of socio-dynamics. No question must remain unanswered, avoiding the argument of authority, in creating the confidence required to “live together” based on reciprocal goodwill and contradictory debate. This is the ABC of the correct organization of interactions, in some way a “geometry of cognitive entity”[47] that takes into account the world as it is.

This double requirement, construction and explanation, must allow us to look at the complexity of the situations that we are already facing, such as global warming or the correct management of nonrenewable resources, with a good chance of success. The somber predictions made in the Meadows report, “The Limits to Growth”, violently contested by many economists (including in France by the former Prime Minister R. Barre) when it was published by the Club de Rome in 1972 are now almost a reality[48], above all concerning the pollution of ecosystems because for the moment we do not repurpose the waste we produce. Its main results could be reworked using simulation capacities with no comparison to those of the 1970s that were implemented by J. Forrester at the MIT. Non-controlled development leads to harm such as pollution, an inconsiderate waste of fossil energies creates imbalances that can have a global effect on the Earth’s ecosystem. There is nothing in this that is truly original to invent, but the problem and the questions still need to be taken in the right order. Anyone who has been confronted by the problem of engineering of complex systems knows that the order in which the questions need to be tackled both dictates the dimensioning and is imperative. At this scale, any problems that are badly laid out, with uncertain data, rapidly become an inextricable combinatory nightmare. Maturity cannot be ordained; it is constructed step by step, by a long learning process. Cognitive psychology, the stages by which our intelligence develops, the need for cooperation between humans[49], has in fact explained it very well. It is necessary to convince ourselves of it, however without conceding our critical thinking and our vigilance that need to be used at the right moment to validate or disprove the hypotheses in the model.

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[46] In Chapter IV, “On structure”, of his book *Science and Sanity*, 5th edition, 1994.

[47] I have borrowed this term from the logician J.-Y. Girard; refer to his website.

[48] Refer to D. Meadows *et al.*, *Beyond the Limits*, 1992; and also R. Kurzweil, *The Singularity is Near*, Penguin, 2005, to return to a degree of optimism, but to be manipulated with a pinch of salt because he is the Chief scientist for Google, and besides this a hardened militant for transhumanism and H+ humanity.

[49] Refer to the book by M. Nowak, Harvard professor, *Super Cooperators – Beyond the Survival of the Fittest; Why Cooperation, Not Competition, is the Key to Life*, Canongate books, 2011.

Nothing is ever acquired definitively, structures are subject to “wear”, entropy and a *laissez-faire* approach mechanically fabricate undifferentiated disorder no matter what happens. None of the natural or artificial processes escape this and everything is reformulated because the situation itself evolves. Fate and chance are not involved, nor are poker players, but the contingency that reshuffles the cards does indeed have a role to play.

It must be possible to teach the method of resolving problems in complex situations, this fifth discipline, both in major engineering schools and in business schools, and in a general manner where decision-makers are educated, reflecting on scenarios like those evoked in this introduction. All will be faced sooner or later with situations where only collective intelligence will be able to give answers that are acceptable for the masses. For this, the method must be “decontextualized” (in computer science, we would say context free), meaning a generalization to simplify it, so as to bring out the concepts that underlie it, but never losing the connection with reality, which neutralized it immediately. This collective intelligence is more than a simple addition; it is an integration of skills that emerge thanks to the organized interactions of the various disciplinary fields, human sciences included. The sociodynamic aspects are fundamentally in the human “energy” of large projects, clearly brought to light by J.W. Forrester. “More is different” said the Nobel prizewinner P. Anderson in an article that has remained famous, and this is what we need to prepare ourselves for in sciences of engineering of open systems of the 21st Century in which human beings, more than ever, have a large role to play.

In A. Grothendieck’s autobiography – a true genius of mathematics who died in 2014, and a re-founder of modern algebraic geometry, page 48 of *Récoltes et semailles*[50] – there is an entirely illustrative small text of the method to put into practice for whoever wants to be seriously faced with the systems that surround us on all sides: those that we create and those that are given to us by nature. We can take it as it comes, without changing a single word, to make systemics a tool for analysis and communication that is useful for everyone, for a common good:

> “The structure of a thing is not at all something that we can ‘invent’. We can only patiently update it, humbly find out about it, ‘discover’ it. If there is inventiveness in this work, and if it so happens that we do the work of a blacksmith or a tireless constructor, this is not at all to ‘shape’ or to ‘build structures’. These have not waited for us before coming into being, and to be exactly what they are! But this is in order to express, as loyally as we can, these things that we are in the process of discovering and finding out about, and this structure that is reticent to reveal itself, that we are trying to sound out and to grasp with a

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[50] Only available on the Internet.

> language that is perhaps still stuttering. Thus we are led to constantly ‘invent’ the suitable language to express more and more finely the detailed structure of mathematical things, and to ‘construct’ the ‘theories’ that are supposed to recount what has been understood and seen, with the help of this language, gradually and entirely. Here there is a continuous, uninterrupted movement of coming and going, between the apprehension of things and the expression of what is apprehended, by a language that is refined and recreated as work goes on, under the constant pressure of immediate requirement.”

What more can we say, we must create the grammar of this new multi-faceted language.

Systemics, science of control and equilibrium of systems, science of the finality and integration of processes that nature provides and in which we have the role of interested parties, as a function of a clearly specified and assumed objective (the heart of the model, its fundamental invariant that makes it exist as an individualized distinct system) in a contingent environment that is locally unpredictable, but globally deterministic and where there are rules and order like those taught to us by physics must at last find the place that Norbert Wiener and his colleagues had assigned to him, a place in the front row, to resolve the global problems that our globalized and open society is now confronted by. The solutions can only be local and cooperative. There can be no single center, because *one* single center is a point of fragility that is incompatible with a robust human society faced with internal and/or external hazards, resilient, capable of evolving without destroying itself, meaning truly durable. Cooperate or perish, continuously adapt, this is the question, and also the message of hope of the solution brought by systemics and its new language that provides us with the key to how to proceed. In many ways, this beginning of the 21st Century resembles the 1950s, full of risks and promises. If we do not organize complexity, complexity will destroy us slowly but surely.

1.4. Education: systemics at MIT

As an example, we give a brief view of the chronology and the main changes in teaching systems science at MIT, not by open-mouthed admiration of this famous institution, but to encourage those who have the heavy responsibility of organizing engineering teaching in France to reflect. The continuity of effort is impressive, with no equivalent in France, unless we go back to the era of the beginning of the Industrial Revolution and to the foundation of the large engineering schools – away from the university that did not want these disciplines to be considered ancillary (to remain polite!).

Officially founded in 1998, the ESD (Engineering Systems Division) has been entrenched in an interdisciplinary approach to systems engineering problems over the course of decades of development.

1948	**MIT, professor N. Wiener published *Cybernetics***
1954	H.M. Paynter implemented the first classes in systemics
1961	**MIT, Sloan School, J. Forrester published *Industrial Dynamics***
1971	A.H. Keil implemented the Center for Policy Alternatives
1973	Foundation of the Center for Transportation Studies
1975	Foundation of the Technology and Policy Program
1985	Creation of the Center for Technology, Policy, and Industrial Development
1988	Launch of the leadership program for Manufacturing
1989	The MIT commission on *Industrial Productivity* publishes its report “Made in America”
1991	Implementation of the doctoral school *Technology, Management, and Policy* (TMP)
1993	The engineering school at MIT published *Engineering with a Big E*
1996	The Eagar committee recommended creation of the *Engineering Systems Division* (ESD)
1996	The MIT program *System Design and Management* was founded
1998	Implementation of a *Master of Engineering in Logistics*
1998	**Foundation of the *Engineering Systems Division* (ESD)**
2000	First double-capacity chair recruited by the ESD
2004	**First international symposium on systems engineering (*Engineering Systems*) at the MIT**
2004	Introduction to the *ESD Doctoral Program* incorporating the TMP

2004	**Implementation of an interuniversity council for engineering systems**
2008	Recruitment of two new double-expertise chairs at the ESD
2009	Merger at the ESD of the architecture and the planning schools; the ESD division is now present in the five MIT schools
2009	The biomedical innovation center (Center for Biomedical Innovation) at the MIT joins the ESD
2009	**Second international symposium on systems engineering (*Engineering Systems*) at the MIT**

Box 1.2. *The long continuous history of teaching systemics at MIT (the full original version of this box is available on the authors' website[51])*

In France, to have an equivalent critical mass, it is necessary to imagine a coordinated merging of teaching at the Ecole Polytechnique and its application colleges, in broad terms ParisTech, Ecole Centrale, including the intergroup, and SupÉlec which have also just merged together, and business schools such as INSEAD, HEC or ESSEC; not forgetting the CNAM and "life-long" learning. In the past, the situation was different due to the dispersion of strengths and to "Gallic" rivalries, but the accomplishments were impressive, at least during the 30-year post-war boom in France, which is of principal importance, but at the cost of a considerable waste of energy.

The digital revolution and the revolution of *en masse* computerization, the omnipresence of MOOCs, is going to require revisions to the foundations of teaching in engineering where the science of systems will occupy a principal position. It is therefore time to "get down to it" before it is too late, to avoid relegation.

The factor that has made the MIT what it is, amongst other factors, is a desire to stay awake and alert.

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[51] Available at http://www.cesames.net/.