EDITORIAL

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Medicine and the Sciences of Complexity

Some years ago, physicist S. Hawking was asked his point of view about the highly prevalent opinion that described the twentieth century as the century of biology, while the twenty first was touted as the century of physics. Hawking replied that, in his opinion, the twenty first century would be the century of complexity.

Even while some privileged thinkers like H. Poincaré (1892) or G. Julia (1918) managed, towards the end of the nineteenth century, to surmise the intricate structures of certain mathematical systems which, with the passage of time, morphed into paradigmatic examples of complex systems, it wasn't until the last third of the twentieth century, with the coming of age of digital computers, that the conditions were ripe for in depth investigation of systems whose complexity had defied the tools available at the time. Just as Galileo's telescope changed the whole picture of astronomy and the very conception of its contemporary world, digital computers opened up a whole new universe to the scrutiny of scientists at the beginning of the twenty first century (Pagels 1989). We have reached the possibility of investigating the structures of complexity in the different levels of organization of matter, from molecular strata to population conglomerates.

This is particularly evident in the field of the medical sciences. The human body is, without a doubt, a system of systems, a paradigmatic vision of complexity at different scales. Both its nervous systems (sympathetic and parasympathetic), its endocrine, respiratory, gastro-intestinal systems, to mention just a few of the better known, make our bodies probably one of the greatest accumulations of interconnected and interwoven structures in all nature, barely rivalled by other living species. Our organism possesses such a complex structure that it has enabled the appearance of the emergent trait we call awareness, so far the exclusive patrimony of our species in the whole universe. It is the complex system *par excellence*.

Some researchers regarded this massive structure with eager anticipation, but without the appropriate instruments were unable to work out all the details

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of such a colossal fresco. One of these pioneers was French scientist C. Bernal. In his 1865 work *Introduction to Experimental Medicine,* he presented the concept of homeostasis, attempting to explain the stability of the functions of the human body. Homeostasis can be viewed as resistance to change, and is a general characteristic of all highly complex systems. It is the method that nature has developed to maintain the internal state of the human body and other similar systems (Aréchiga 2000).

However, for centuries the medical sciences oscillated between medieval obscurantism—that tended to consider diseases as divine punishment for the sins of human beings (Rosen 2014)—and the ideology emerging from the Industrial Revolution, that transfigured the basic concepts of medical sciences and the perception of health into a series of purely quantitative measurements, that should be expressed in perfectly established intervals, just as machines sustain their functions according to underlying parameters with predetermined tolerance intervals. The assumption of linearity between cause and effect became dominant in the medical sciences and their procedures (West 2006).

Average values reaffirmed their dominance

The average temperature of the body, the average respiratory rate, and the average heartbeat, warned the doctor if the patient was sick. There was no room for fluctuations in this proposal. A fundamentally linear model arrived at the conclusion that fluctuations do not contain useful information. This was very visible in A. Quetelet's work (*Sur l'homme et le development de ses facultés. Essai d'une physique sociale*, 1835), when he used Gaussian distribution to explain deviations from the values of "average man", not only as a philosophical abstraction, but as biological reality too, a result of genetics and evolution. He interpreted human variability as an error, in a similar manner that Gauss interpreted errors of physical measurements. This type of reasoning was not lost on the physicians of the time. This was, without a doubt, the beginning of the incomprehension of complexity in the medical sciences.

The frontiers within this ordered world started to crumble towards the end of the nineteenth century with, as we have mentioned, the work of H. Poincaré, who discovered the footprints of chaos within the synchronous world of Newtonian gravity. This, along with observations made by R. Brown in 1827 concerning the movement of microscopic particles, and the research by H. von Helmholtz, E Weber, C. Ludwig and J. Müller in Germany during the 1840s, clearly established the idea that reductionism, which had worked so well for the construction of machines, didn't seem to apply when it came to explaining biological systems.

New paradigms: complexity

The last phase of this revolution started with the work of E. Lorenz (1963) on deterministic non-periodic flow in the atmosphere. For the first time, "details" that had been disdained by scientists and termed "noise" or "perturbation", were receiving the attention they really deserved in the non-linear formulations that—thanks to the explosion in the processing capacity of digital computers—were now accessible to the scrutiny and application of researchers.

One of the most important discoveries of those times was made by M. Feigenbaum (1978). By means of numeric simulations he established the scales in which the so-called "doubling periods"[1] should occur in the path to chaos. It is remarkable that one of the first experimental confirmations of this theoretical result should have occurred in the field of physiology. M. Guevara, L. Glass and A. Shrier (1981) showed that, by electrically stimulating heart cells in chicken embryos they could observe responses that followed the pattern of doubling periods discovered by Feigenbaum. The increase in the use of medical equipment that interfaces with digital devices has explosively increased the quantity and the quality of physiological data. No doubt, this has resulted in better comprehension of the systems that make up the human body. We submit some examples: the studies related to the functions of the brain and the heart, and their unique rhythms, and the sequencing and manipulation of long chains of DNA, are achievements that could only be possible due to the availability of digital devices, that have provided a degree of precision in the study of these structures that had never been available before. Similarly, the possibility of understanding epidemic phenomena has depended on our capacity to simulate them.

The paradigms emerging from the Complex Systems theory have also influenced other phenomena linked to the transition between health and illness and to the nature of health systems. The management of health institutions has suffered, from the conceptual point of view, the same limitations exhibited by the reductionist approach to the study of diseases.

As a consequence of this, between 2003 and 2004, in Mexico, the federal Health Department initiated an ongoing seminar to analyze these issues, with the participation of experts in complexity and health systems. The spectrum of topics covered in these seminars was very broad indeed. From bold models of the

1 There are three ways in which systems may shift towards a chaotic state: the Roulle-Takens route, linked to the emergence of turbulence, the route linked to intermittencies, and the third, that involves period doubling. This last one occurs when trajectories increase the length of their period, doubling it on each occasion, until a critical situation is reached and the system becomes chaotic. It has been detected in a multitude of different phenomena, such as the stimulation of cardiac cells, population dynamics, hydrodynamic turbulence, etc.

evolution of the dynamics of DNA, to novel techniques for studying complex networks, with all that this implies, in various areas of scientific medical work and in the administration of health systems.

As a result of these efforts, a book was published: *Las ciencias de la complejidad y la innovación médica* (Sciences of Complexity and Medical Innovation, Ruelas and Mansilla 2005). Basically, the contents rounded up the original contributions to the original seminar, although it also contained contributions from other specialists. One year later, a sequel appeared: *Las ciencias de la complejidad y la atención médica: ensayos y modelos* (Sciences of Complexity and Medical Innovation: Trials and Models, Ruelas, Mansilla and Rosado 2006). This was, no doubt, a more mature attempt to apply the concepts and paradigms of the Complex Systems Theory to different fields in the medical sciences. However, it was still in the stage of good wishes and intentions. It was imperative to design a method for summing up and measuring the results of the process. A decade later, while celebrating a hundred and fifty years of the foundation of the Mexican National Academy of Medicine, a new editorial project was presented, that covered different analytical perspectives: individual illness, disease from an epidemiological perspective, health care organizations, and health systems. The title, congruent with its predecessors: *Las ciencias de la complejidad y la innovación médica: Aplicaciones* (Sciences of Complexity and Medical Innovation: Applications, Ruelas and Mansilla 2015).

In the field of education, the postgraduate course in Medicine and Science of Complexity was initiated in 2009. It is a joint effort by the Center for Interdisciplinary Research in the Sciences and Humanities (CEIICH in Spanish) and the School of Medicine at Mexico National Autonomous University (UNAM in Spanish) and other institutions. It covers basic issues emerging from the Complexity Theory and their application in different branches of the medical sciences. Targeted initially at health professionals, it has also attracted a broad range of social scientists, as well as physicists and mathematicians interested in applying Complexity Theory methods to the health sciences.

At present, it seems impossible to reject the methods emerging from Complexity Theory if we wish to enrich our understanding of the processes linked to health and disease. The success of medical research in the future will depend upon the level of comprehension by health personnel of the new paradigms emerging from this Theory. Id

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