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# The Digital Revolution in empirical science



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## Abstract

In this article I argue in favor of the thesis that the transition from analogue to digital experimental work can be considered as a revolutionary change. This is particularly evident in the context of the revolution criteria proposed by Hacking, Kuhn's findings, however considering the changes in the theories, are also helpful when arguing in favor of the thesis. The use of the computer has certainly revolutionized the experimental study across multiple scientific disciplines.

**Keywords:** philosophy of experiment, digital support of experimental research, scientific revolution.

## Introduction

The development of computers, software and peripheral devices has enabled, the use of these devices in almost all areas of human activity, particularly since the early eighties. This has given rise to a number of radical social and cultural changes. They are known at present as the digital revolution in civilization. It is worth noting that the widely described digital revolution in civilization has trivialized the revolution in science which had taken place thanks to computers. Perhaps it is not so that the digital revolution in experimental studies is merely a consequence of the earlier digital revolution in civilization.

Constructing the computer (ENIAC) was, after all, the result of military scientific demands which included the calculations of trajectories, simulations of chain reactions, designing wind tunnels, as much as studying cosmic rays *etc*. The emerging of the Internet was also a consequence of military scientific inspirations (Advenced Research Projects Agency has initiated the formation of the first ARPANET which merged together four research centers carrying out military research in the United States: the University of California in Los Angeles and Santa Barbara, the University of Utah in Salt Lake City and the University of Stanford in Menlo Park.) The emergence of web technology which has revolutionized and virtualized social relationships, is no longer only the result of the needs of researchers (scientists in CERN created a design of a network of hypertext documents called the World Wide Web). Creation of this arrangement was inspired by the idea of facilitating the search of links in scientific texts (a click on the link in the scientific text enabled automatic advance to the cited document). Therefore, the digital revolution might be rather a consequence of the digital revolution in experimental studies. But can we indeed talk about the digital revolution in experimental studies?

Later I shall provide answers to this question by referring to two concepts of scientific revolutions – one by Thomas Samuel Kuhn and another by Ian Hacking. The answer to these questions will become possible when the criteria of scientific revolutions proposed by the authors already mentioned are referred to the change caused by the transition from analogue to digital methods of research (experimentation).

In my article I will, therefore, strive to defend the thesis that the computer has revolutionized experimental research with the inclusion of new digital elements (analogue-to-digital and digital-to-analogue converters, interfaces, computer and software) in the experimental system. Without any computer support many crucial contemporary scientific experiments could not be carried out and that is for two main reasons which I shall mention in the next chapter. This is most well observable in the case of the study apparatus called the Large Hadron Collider (the LHC) installed in CERN[1]. In this article I will show, therefore, that the computer enables modern experimental studies.

## Experimental computer-supported model (LHC in CERN)

In today's computer-supported experimental models one can distinguish several hardware elements constituting one functional unit. Information from the object of experimental studies is collected by means of measuring devices (sensors). Subsequently, this analogue information is pre-processed with the use of analogue-to-digital converters. Then, the digitalized data is transferred via various types of interfaces to a computer. It is there that the information - as a result of using specific software - can be processed, stored and made available (eg. in the form of visualization). Computers together with software can also control the course of the experiment (via interfaces, digital-to-analogue converters and actuators)[2].

The easiest way to trace the significant role of the computer as a device enabling today's experimental research is to study the of example of the largest laboratory in the field of particle physics, that is CERN, and the latest research conducted there known, in 2012 as the results of a pursuit for the Higgs boson in the experiments carried out in the LHC (Aad, Abbott, Abdallah, J. et al., 2012; Chatrchyan, Khachatryan, Sirunyan, et al., 2012).

1 The LHC is an accelerator in which beams of particles collide (hadrons - protons and ions - are subjected to acceleration). The technical details concerning the construction of the LHC can be found in an extensive article by J. Kulka (2009).

2 A detailed description of the elements of experimental computer-supported model can be found in the book by Leciejewski (2013), pp.36-61.

One should, however, ask whether this type of empirical breakthrough could have taken place without computer-supported experimental studies[3]? The answer to this question seems obvious: without computer support most of today's experiments would fail to be performed as in this type of experiment we deal with too much data released simultaneously by too many measuring devices.

In the LHC about 150 million sensors provide experimental data at a frequency of 40 million times per second. After filtration (to delete standard cases which are already known) one can obtain about 100 interesting collisions per second. The transfer rate of data is 700 MB / s (ie. approximately 15 000 000 GB per year). Such large amounts of data would be able to be received and stored by no other system other than a computer system. Therefore, without computer support it is not possible to download the empirical data obtained in modern scientific experiments. Without it there is also no way to precisely control the course of this type of experiment.

Particles circulate in the accelerator inside a vacuum tube and are controlled by electromagnetic devices. Therefore, the system controlling the beam in the LHC can be precise and quick enough to be able to obtain the number of about 10 000 laps (each lap is about 27 km) and 600 million collisions per second. Protons circulate in the LHC around the ring in specific bunches. These protons can be accelerated only when the electromagnetic field is appropriately oriented while the particles pass through an accelerating cavity which happens only in very specific moments (about 10 000 times per second). Such precise control of a complex experiment would not be possible without a computer-supported system of experimental studies. Without it, it would be impossible to obtain any significant experimental results, among which there are undoubtedly those mentioned at the beginning of this chapter.

The acquisition of such important results was possible thanks to the fact that in CERN there is an adequate research apparatus (the LHC). Some extremely complex physical experiments are being conducted there and - most importantly in the context of the issues undertaken in this chapter - computer systems of acquisition, archiving, and analysis coming from data detectors are also in use. One of such distributed systems of analysis of data from experiments is called WLCG (Worldwide Large Hadron Collider Computing Grid). In order to achieve important results, *eg*. the discovery of the Higgs boson, the local computing resources of CERN computer center fail to be any longer sufficient, although they are still impressive (65 000 processors, 62 PB of disc storage[4]). However, they represent only about 20% of the needed processing power.

CERN computer resources *(ie*. Tier-0) serve merely to record experimental data, primarily process empirical data (*eg*. deleting well known cases of standard collisions) and their distribution to the next levels of a widespread network

3 Computer support of experimental research is a „whole group of methods and measures meant to improve, with the general objectives of experiment (scientific, technical, medical, etc.), the retrieving of information concerning the examined object and its processing by means of computer technology." Kulikowski (1993) p . 8.

4 1 PB (petabyte), *ie*. 1024 TB (terabyte), *ie*. 1024*1024 GB (gigabyte), *ie*. approximately 1 000 000 GB.

used for storing and analyzing data obtained from the LHC ( *ie*. Tier-1 and Tier-2). Tier-1 constitutes eleven data centers in Europe and the United States, which archive data from the LHC, perform preliminary calculations and analyses of collected material; whereas Tier-2 includes 140 smaller data centers located in 34 countries around the world which deal with conducting computer simulations based on empirical data collected in the Tier-0 and Tier-1 and the final data analysis carried out online by more than 8 000 physicists. With such infrastructure, scientists from around the globe who study the physics of elementary particles are able to obtain access, via the Internet connection, to the data produced by the LHC and to their analysis almost in real time.

Obtaining results considering the discovery of the Higgs boson required the use of several computer programs (Aad, Abajyan, Abbott, et. al., 2012, p. 2), the entire computing power of Tier-0, seven computing centers of Tier-1 and fifty centers of Tier-2 ( Aad, Abajyan, Abbott, et. al., 2012, p. 31) in which 300 000 processors analyzed 30 PB of data for about two years under the supervision of 2 800 scientists from 178 research centers (Aad, Abajyan, Abbott, et. al. , 2012. pp.17-18). It is worth recalling that 1 PB of data constitutes 1 125 899 906 842 624 bytes (one byte is 8 bits), and they had to analyze 30 times more data. The mere reading of 30 PB of data, assuming that one is able to read through 100 pages of text per day, would take about 500 billion years. The amount of information is so unimaginably huge that, without the use of computing power approximately equal to 300 000 computers scattered all over the world and communicating via the Internet, it would be impossible to analyze them. It can, therefore, be concluded that the LHC in CERN could not function without computer support. Without the use of computers it would be impossible to proceed towards such cognitively significant results as those obtained in CERN between 2011-2012.

Therefore, without computer support many momentous contemporary scientific experiments could not be carried out, and that is for two reasons. We are dealing with too much empirical data coming simultaneously from too many measuring devices; what is more, conducting experimental research today is related to the need for using highly precise systems of controlling complex actuators. In order, therefore, to conduct crucial cognitive experimental research today, the computer is utterly indispensable as an essential part of the experimental model. Its task is to precisely control the course of the experiment and swiftly download any empirical data from multiple measurement devices. The computer, thus, makes contemporary experimental research possible. It is also a device that has revolutionized scientific research.

## Criteria of the revolution in science by Kuhn and Hacking

The author of the best-known classical model of scientific revolution presented in 1962 in his work *The Structure of Scientific Revolutions*, is Thomas S. Kuhn. His views are so well known that I shall not discuss them in detail. I will cite only these threads of his work which will be used to answer the question stated in the title of the next chapter.

According to T. Kuhn in the period of the so-called normal science it is constituted by some paradigm. “The paradigm sets the boundaries for normal science, and normal science updates and articulates the paradigm. The paradigm does not always fit the experimental results. There are discrepancies, that is anomalies. The practice of normal science relies heavily on resolving these anomalies by making appropriate amendments which do not violate the same paradigm. (...) Only when negative test results will begin to multiply, they may be increasingly recognized as arguments against the theory itself (...). When such opinion is beginning to be visible among the community of scholars, the period of extraordinary, revolutionary science begins. It lasts a relatively short time and ends either in returning to the old, but already improved paradigm or in scientific revolution leading to a new paradigm” (Jodkowski, 1990, pp.134-135).

The concept of a paradigm is, unfortunately, ambiguous. Its definition, given by Kuhn, states: Paradigms are “universally recognized scientific achievements which, in some time, provide the community of scholars with model problems and solutions”. (Kuhn, 2009, p.10.) According to Kazimierz Jodkowski, Kuhn’s paradigm can be generally understood as “tradition of research, thread of thoughts, which carries a number of tips for a group of scholars, how they should approach the phenomena, how to analyze them, what kind of effects they should expect, what types of experiments to conduct and which collection of methods to use. Paradigm provides a way of seeing the problem and suggests what kinds of techniques are appropriate and what types of solutions acceptable” (Jodkowski, 1990, p.140).

Currently, there are two basic meanings of the term “paradigm”. First is the so-called matrix of scientific discipline. It is a set of beliefs, values and techniques shared by members of a scientific community. Kuhn mentioned four typical components of a matrix of scientific discipline: symbolic generalizations, metaphysical beliefs, theoretical values and model solutions (patterns of solving puzzles). T. Kuhn made his patterns a second kind of paradigm (Jodkowski, 1990, pp.143-147). In other words, the paradigm, in a broader sense, is a set of beliefs, values and scientific techniques maintained in the scientific community. In the narrow sense it is included in the previous and it is the pattern of solving problems. Thanks to the set of specific example solutions, a scholar, on the basis of normal science, solves the newly encountered problems.

T. Kuhn believes that succeeding theories, separated by a scientific revolution, are disproportionate, *ie.*, in a sense different, varying, incomparable. Normal changes in science rely on a cumulative increase of knowledge, adding new to the already existing. On the other hand, changes of a revolutionary nature relate to discoveries which cannot be described by concepts used prior to these discoveries. One cannot enrich science with this revolutionary discovery and this discovery cannot be made without changing the ways of thinking and describing a range of natural phenomena. “In most cases, revolution is preceded by crisis – a widespread awareness within the group of scholars that the practice of normal science is facing more and more difficulties, anomalies. But this crisis is not always necessary. Sometimes revolution is triggered by the application of a new research instrument, such as an electron microscope, or theoretical, *eg*. Maxwell's laws, which have been developed among a different field, inside another paradigm" (Jodkowski, 1990, p.174).

T. Kuhn did notice the fact that the improvement of measuring and research equipment has an impact on scientific theories, however, he failed to appreciate properly the importance of developing scientific equipment. In his *Structure of scientific revolutions* he himself points out that, besides some minor remarks, he does not discuss the role which technical progress plays in the development of science (Kuhn, 2009, p.13). He, however, supposes that "the exact examining of these issues (...) would deepen the analysis and understanding of scientific progress significantly" (Kuhn, 2009, p.13-14).

Ian Hacking is a philosopher of science, who is definitely more inclined to highlight the influence of research equipment on the cognitive changes of science. In his article *On the Stability of the Laboratory Sciences* (Hacking, 1988, pp. 507-514) he lists four essential characteristics of scientific revolutions. Firstly, they are interdisciplinary or pre-disciplinary. Secondly, on their basis grows new social institutions of both scientific and industrial characteristics. Thirdly, such revolutions result in quite radical changes in the structure of science. It is followed by the reorganization of the society of science. Fourthly, these revolutions entail some fairly significant changes in our worldview and our cognitive relation to the world.

For T. Kuhn, therefore, experimental science facilities are only there to fulfill a supporting role for breakthroughs in the field of theoretical description of the world, while Hacking speaks of revolutions in science as revolutions of apparatus, *ie*. those which refer to radical changes of research instruments used by scientists. These revolutionary changes in science are not only epistemological (cognitive), but also ontological (concerning existence). The new equipment not only enables more accurate study of the world but it can also create entirely new phenomena, as yet non-existent in nature.

## Has the computer revolutionized experimental studies?

The first concept of revolution in science, mentioned in the previous chapter, was formulated by T. Kuhn. If his paradigm is to be understood in the narrower sense, as a model of solving specific problems accepted by the scientific community, then it is possible to use the concept of revolutionary change which is based on it as the reformulation of such a pattern, in order to find the answer to the question put forward in the title of this very chapter. The answer obtained will certainly not be conclusive, as T. Kuhn's considerations are related essentially to revolutionary changes in theories. He fails to analyze properly the experimental work and the related issues. However, if one takes into account the instrumental criteria of progress in science, *eg*. the ability to construct and solve puzzles, it becomes evident that the potential in this field of computer-supported experimental studies is much greater than that of research carried out without such support. The new paradigm usually explains more of them and more accurately than the old one, and that has clearly been the case with computer-supported experimental models.

Thus, the use of computers in empirical science would be revolutionary if most of the scientific issues were to be resolved with the use of computer systems. And with just such a phenomenon we are presented since the eighties, when the use of computer-supported systems in empirical science became common. Today, the majority of this type of research is conducted with the use of computers. In addition, computers are research tools enabling today's experimental studies (about which I wrote above). Thus, even if the revolution were to be understood as a change in the pattern of solving scientific problems with instrumental criteria of progress taken into account, undoubtedly we are dealing with significant progress in the case of computer-supported experimental studies, and the transition from analogue to digital empirical studies can be considered a revolutionary change, for the way of solving specific research problems has changed completely.

It is worth remembering that today these are not the experimenters themselves but computers they program which precisely control the flow of experiments, collect empirical data and store it. Processing of empirical data is also carried out using specific computer programs and some simple phenomenological laws can be formulated without the participation of an experimenting entity (Giza, 2016). So today we are dealing with a computer model of solving scientific problems. Without the introduction of computers to the experimental system many problems would fail to be solved, and even put forward (*eg*. the problem of the energy value of the Higgs boson).

Another very interesting proposition of understanding the problem of revolution in science is, cited in the previous chapter, Hacking's concept. This author, as I already mentioned, and what is worth emphasizing, lists four essential components of scientific revolutions which are not purely theoretical. It is not difficult to see that the use of computer support in experimental studies with good approximation satisfies the assumptions made by Hacking on the revolutionary changes in the study apparatus. The Computer is certainly an interdisciplinary research tool. It is used widely in all the empirical sciences as a tool supporting experimental research and used for numerical analysis of the results. Moreover, in all the sciences (including humanities) it is the tool with the use of which the results are presented (*eg*. via various media), and which constitutes the means of communication with other research centers (via Internet).

The use of computers in experimental research has also led to some massive changes in the production and distribution of research equipment. It has resulted in the emergence of specialized companies (*eg*. National Instruments), which produce measuring instruments constituting functional wholes composed of measuring devices, analogue-to-digital converters and interfaces. They are specially designed in order to work with computers. In addition, at present there are also software forms involved in the design and implementation of software used exclusively to support experimental research (*eg*. LabVIEW). What is more, entirely new scientific institutions have also been created and their aim is to provide access to the computing power of supercomputers adapted to the scientific number analyses (*eg*. the Worldwide Large Hadron Collider Computing Grid mentioned above).

Computers used in experimental research have also led to some radical changes in the structure of science, *ie*. to the reorganization of the society of science. Today some individual, local research centers are of much less relevance and almost all of the important studies are conducted in inter-university, international, global, enormous research projects whose existence is based on two main pillars. The experimental work is carried out in huge, computerized research centers and any obtained empirical data is analyzed thanks to the electronic communication of scientists from all around the globe. This is evident in the example of the LHC in CERN as much as the Worldwide Large Hadron Collider Computing Grid (as described above).

The emergence of new scientific sub-disciplines is also present, for example computer physics dealing with the use of computers in physical research. Its emergence was only possible when computers had obtained the appropriate computational power and become widely available. The object of its interests can be divided into two distinct parts: theoretical computer physics whose main area of activity is solving physical problems by the means of numerical methods (computer simulations) and experimental computer physics which deals with the use of computers in physical experiments (the LHC).

Hacking also argues that revolutions in the research apparatus entail quite significant changes in our worldview and cognitive relation to the world. The use of computers in empirical studies has changed not only the image of the world, but the Universe as well. Thanks to computerized research equipment it has become possible to study with unprecedented accuracy, *eg*. the so-called background radiation (which made it possible to estimate the age of the Universe with high accuracy), the existence of black holes in the centers of galaxies, the accelerated expansion of the Universe and many other phenomena.

It is, therefore, to be concluded that using the criteria of revolution in science proposed by Hacking, one can formulate a thesis that the computer has revolutionized the experimental studies, since the introduction of this research tool undoubtedly is interdisciplinary. In connection with the use of computers in empirical science emerge new social institutions and radical changes occur in the structure of science. This revolution also entails fairly significant changes in our worldview, as much as our cognitive relation to the world.

## Summary

The development of computers, software and peripheral devices has enabled us to perform computing, controlling, consulting, diagnostic, monitoring, measuring, navigating functions in a more effective way; It has led to their use in almost all areas of human activity. The emergence of increasingly advanced computers

has enabled the development of computer science itself which is a connection of various theoretical fields (mathematical methods, logic, theory of automata, theory of algorithms, mathematical linguistics), as much as technical (construction of hardware, software development) and applicational (application in various fields). One of the most important applications has become the supporting of research in the empirical sciences. Computers have been used for such purposes since the forties, beginning with the predominance of military applications. Gradually, computer-supported research ceased to be exclusively mandated by the military, and it has become research without military connotation. In the eighties, computer-supported experimental research has become the standard in research work carried out in most prestigious scientific laboratories.

It is, therefore, worth highlighting once again that modern experimental studies can be and are conducted mainly with the use of computers. This transition from analogue to digital experimental work can be considered a revolutionary change. It is particularly well evident in the context of the revolution criteria proposed by Hacking, although oriented towards the changes in theories, suggestions made by Kuhn are also helpful in order to argue in favor of this thesis. It seems, therefore, that a positive answer to the question included in the title of the previous chapter can be considered sufficiently justified. Indeed, there is no doubt that the the computer is very much involved in the process of modern scientific research. It sets a new, *ie*. computer research style (Leciejewski, 2013, pp. 115-121). The use of the computer has certainly revolutionized the experimental research across multiple scientific disciplines. Thus, in the second half of the twentieth century there has appeared an important change, which could be called the digital revolution in empirical science.

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