"In silico" Experiments:
Towards a Computerized Epistemology

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Making a Brief Latin Revival

It would seem that it is thanks to computers that Latin, a so-called dead language, is today enjoying a brief revival. At the end of the eighties (cf. http://en.wikipedia.org/wiki/In_silico), biologists who wanted to give a name to experiments performed using computers or, to be more precise, using the silicon microchips that constitute the core of computers invented a new Latin idiom, *in silico*. The expression was built by analogy from – and in contrast to –*in vivo* experiments, i.e. experiments on living organisms, and *in vitro* experiments that bind biological mechanisms to chemical processes reproduced in glass test-tubes.

Some purists (Quinion, 2006) seem to be unhappy with this new idiom because, strictly speaking, linguistic rules which could have been emulated on a computer would have given the neologism *in silicio* from the Latin word *silicium* which means silicon in English. Nevertheless, usage has imposed the idiom *in silico* which is widely accepted today. Although computers led to a brief Latin revival through the invention of a new Latin idiom, this was however due neither to a computer simulation, nor to an informational operation, but to a new formulation of old questions because of the generalized use of digital processors. In a way, we find the same thing in contemporary epistemology: with computerization this discipline evolves, but this is due not only to an informational or to a computational model of epistemology, but also to the increasing role that computers play in science in general, and to the increasing role they could play in epistemology in particular. This article constitutes an attempt to highlight this role.

Naturalization vs. Computerization

Recently, there have been attempts to naturalize epistemology with computers, i.e. to use information theory or computational models to explain how science and knowledge change (Dodig-Crnkovic 2007; Chaitin 2006). The proposition is that a general model of knowledge and of its evolution, which is what epistemology is all about, can be grounded on digital computation and information theory. The underlying idea is not new and comes from Leibniz and Hobbes, to name but two. The principle on which all these endeavors are based is that we really understand something if we are able to compute it. Since Alan Turing's famous article on computable numbers (Turing 1936), we know that all computations can be executed on programmable digital machines. Therefore, one of the consequences of the above principle is that we understand something if we can program it on digital machines. Thus, the attempts to naturalize epistemology can be assimilated to efforts to build a digital epistemology (Chaitin 2006).

Our present goal is more modest: it is not to contribute directly to an informational or computational naturalization of epistemology, but to start from the observation that today computers are everywhere, and this transforms both scientific practices and epistemology. In other words, the way we understand the world is greatly influenced by the general use of digital computers, which is not the same as saying that understanding is computing. Since all facts are now reduced to information sets and recorded on huge memory devices, it is possible to directly test theories on recorded data without having to carry out experiments evaluating all of them in the outside world. Undoubtedly, this changes scientific activity, at least in part, and many real world experiments no longer need to be performed, which seems highly desirable for economic and ecological reasons. Consequently, the general use of *in silico* experiments will have to be promoted. But, the exact status of these *in silico* experiments and the validity of the knowledge the scientists infer are open questions of epistemology. In a way, *in silico* experiments are similar to "thought experiments" (Mach 1976; Sorensen 1992; Dennett 1995; Ganascia 2002): both types are achieved outside their object world, in a virtual world which will be mental, for thought experiments, and digital for *in silico* experiments.

In the past, many philosophers – including Karl Popper, one of the most famous – have criticized the role played by "thought experiments" in science (Popper 1959), saying that they did not provide any strong scientific justifications. Some of these philosophers considered these experiments could even be misleading if they picture scientific concepts incorrectly for pedagogical purposes. For instance, Karl Popper criticized what he called the misuse of "thought experiments" in quantum physics (Popper 1959).

Can similar criticisms be leveled at *in silico* experiments? One of the goals of this article is to answer this question. To be more precise, epistemology, understood as the branch of philosophy that studies knowledge and the way knowledge is built, has to take into consideration new scientific procedures that make extensive use of computers. The aim here is to clarify their status and to show that the evolution of epistemology subsequent to the computerization of science will open up new philosophical perspectives.

Actual and Virtual Experiments

Science and the Senses

In ancient times, science was first and foremost a question of observation, and for Plato the most important sense was that of sight. Later on, in modern times, touch took over from sight: people wishing to understand the natural world spent more and more time provoking the subjects they were studying. Thus, in the 16^{th} century, Andreas Vesalius (1514-1564) renewed human anatomy by dissecting the corpses of people condemned to death. Scientific experimentation, in its modern meaning, corresponds to this reversal: it is not enough just to observe, and a scientist will intervene on the world in order first to understand it and then to transform it. This active intervention on the real world continued relentlessly: soon, autopsies no longer satisfied naturalists, who chose to provoke natural phenomena on the living body in order to understand the life springs. They then went further and started performing what are known as *in vivo* experiments because they are carried out on living beings. And so it went on: investigation was not only a question of touching and provoking nature, but also of reconstructing it. This led to the idea of reproducing *in vitro*, i.e. in glass test-tubes, the chemical reactions that are at the origin of the elementary physiological functions.

In the 18th century, some scientists, including Jacques de Vaucanson (1709-1782), created artificial physiologies to get a better understanding of animal functions. Those automata imitated living beings by the means of mechanical devices. Computers are but an extension of this trend: digital data processing techniques can henceforth mimic almost all natural mechanisms, in particular those of living beings, by reducing them to informational processes. This has given birth to a new type of experiment, which no longer has recourse to the external senses but merely unravels sequences of logical operations. As already pointed out, these experiments are said to be *in silico* because they are performed neither on living beings nor on living matter, but on silicon chips which execute logical operations of data processing. In that *in silico* experiments take place virtually, without actually touching the subject under investigation but only altering their representations, they look like virtual experiments, similar to "thought experiments". However, to clarify the actual status of *in silico* experiments and to show how different they are from "thought" experiments and *in vivo* and *in vitro* ones, it would be useful to recall the epistemological status of classical experiments.

Claude Bernard's Closed-Loop Discovery

Claude Bernard (1813-1878) was one of the most eminent 19th century physiologists, and a pioneer in many respects. He introduced the concept of internal environment (the "Milieu intérieur") (Grmek, 1997), which corresponds to today's principle of "homeostasis". He investigated and explained many physiological mechanisms, including the glycogenic liver function (Prochiantz, 1990), the effects of carbon monoxide, (Bernard, 1864; Grmek, 1973), and the effects of curare (Bernard, 1857; Bernard, 1864). But Claude Bernard was not only a great physiologist, he was also a theoretician who generalized his experimental method in his famous book "Experimental Medicine" (Bernard, 1927), which is today a classic that all young medical students are expected to have read.

According to his views, scientific investigation can be reduced neither to the sole observation of facts nor to the construction of theories that have not been previously confirmed by empirical evidence. In other words, Claude Bernard is not an inductivist, who reduces scientific activity to the pure induction of general rules from the observation of particulars, nor is he an idealist – or a neo-Platonist – who thinks that ideal, pure and perfect theories are found before any experiments are carried out. The experimental method he promotes begins with an initial theory, which is usually built from passive observations or preconceived ideas. When the phenomenon is unknown, some experiments are performed just "to see what happens". Claude Bernard does not explain how the first idea or the initial theory is built; it corresponds to an intuition or to what he called a feeling that has to be validated and refined or adjusted according to empirical results generated by appropriate experiments. The experimental method starts there.

Once an initial theory is given, the scientist must design an experimental apparatus able to test (corroborate or refute) it. The experiments are viewed as "provoked" observations generated by an appropriate device and these observations are compared with the expectations derived from the given initial (current) theory. A careful analysis helps to revise, correct, refine or validate the current theory, after which a new experiment is devised to validate the refined theory, and the experimental method is iterated until the theory predicts all current experimental results. In a way, this experimental method is cyclic, which is the reason why it is known as a "closed-loop discovery" process.

To be more precise, the experimental method described by Claude Bernard is an iterative procedure of theory refinement that proceeds in three steps, each step involving a specific scientific function:

Experimentation: a hypothesis that has to be validated has to be given. It is called an idea or a theory. For the sake of clarity, we shall refer to it as the *current theory*. The first step then is to design an experimental apparatus able to generate observations that can be compared to expectations derived from the current theory.

In other words, the experiment is designed to test the hypothesis under investigation, i.e. the current theory.

Observation: the second step involves collecting observations from the designed experiments. It is not only a passive step, since the experimenter may interpret observations and note unexpected details.

Analysis: this third step is the most crucial and original. The current theory predictions are compared to the observations and, where necessary, i.e. when the predictions do not match the experimental observations, new plausible hypotheses are generated to transform the current theory.

Some artificial intelligence research aiming at the computational reconstruction of scientific discovery (Kokabas & Langley, 1998) has focused on a very similar cyclic discovery process. Recent attempts to automate scientific discovery using a "robot scientist" which could generate and test hypothesis by itself also refer to the notion of closed-loop discovery (King *et al.*, 2004). So, this discovery cycle still seems to be valid.

Existence and Role of Mental Experiments

Given this general description of the experimental method, two questions are of interest here. The first is about the existence of virtual experiments in this cyclic discovery process, the second concerns the role they play in the discovery loop.

In the case of Claude Bernard, the answer to both questions is easy: many of his notebooks, for instance the red notebook (Bernard, 1942), contain suggestions for experiments including some that were actually carried out and reported in the laboratory notebooks. These suggestions can be seen as particular cases of mental experiments, which are required preliminaries to any factual experiments. More generally, Ernst Mach argued that a thought experiment was "a necessary precondition for physical experiment" (Mach, 1976). Therefore, a thought experiment takes place once a hypothesis has been put forward, just before a concrete experiment, and its role is twofold. First, it tests the verisimilitude of the hypothesis, i.e. it shows whether or not the hypothesis under investigation is contrary to common sense and our past experience. Second, it helps to design experiments with respect to the current hypotheses, i.e. to build physical devices which will generate the observations that will validate or invalidate a theory. However, it may well happen that, for technical, ecological or ethical reasons, an experiment is impossible, in which case a thought experiment replaces a real world experiment and helps to evaluate the consequences of a theory. As we shall see in the following, to each of these thought experiments correspond some *in silico* experiments that have a similar place in the discovery cycle even if, due to their computational nature, the role they play is different.

However, not all thought experiments are of the type mentioned above. Sometimes, they illustrate theories or the implicit, unexpected or paradoxical consequences of theories; others facilitate communication between the scientists and the public, or among researchers. Since the goal here is not to discuss mental experiments for their own sake, but to look at *in silico* experiments, this last type will not be considered any further, as it does not seem to have any equivalent in the world of computer-aided experiments.

In silico experiments

As we have seen, thought experiments have three main functions in the discovery cycle. The first is to evaluate the verisimilitude of a theory with respect to our past experience; the second is to help design experiments by anticipating the consequences of the conflicting hypotheses; the third is to determine the consequence of the theory when real experiments are not possible. As said above, for each one we find a class of *in silico* experiment. Let us now be more precise.

Informational Experiments

For more then 15 years now, data-mining techniques have been used to test hypotheses against massive quantities of digital information, their explicit goal being to automatically discover knowledge from databases (Klosgen *et al*., 2002). They are based on artificial intelligence techniques that produce many tentative hypotheses and then evaluate each of them with respect to digital data. In a way, these hypothesis evaluations can be seen as experiments, since each of them compares the consequences of a hypothesis to data contained in databases. Because these experiments are done on computers, they are typical cases of *in silico* experiments.

Practical applications of such informational experiments are many and varied. Insurance companies, for instance, use such techniques to help assess individual risks. In scientific activities, it has become necessary to devise systematic informational experiments when huge quantities of data are generated by captors, because there is no other way to give sense to these data. For example, in molecular biology, the linear structure of macromolecules such as DNA or proteins is now determined more or less automatically; the results are stored in huge databases, and computers are required to interpret these enormous amounts of information (Danchin *et al*., 1991).

From an epistemological point of view, informational *in silico* experiments reverse the traditional conception of experimentation. In classical approaches such as Claude Bernard's discovery cycle, the experiment is seen as an active intervention on the natural world and is designed with respect to the theoretical hypothesis it has to validate or invalidate. In a nutshell, first there is the hypothesis, then an experimental apparatus to validate the hypothesis is designed, and lastly data are generated. In other words, empirical data come afterwards. In the case of informational *in silico* experiments, it is the data that come first, after which the hypotheses are generated and tested against the data. The data are collected before the hypothesis has been put forward. In a way, the logic of experimentation has been reversed by the generalized use of computers, which opens up new avenues in science. In medicine, for instance, this could transform clinical evaluation, which would be able to use all existing patient databases.

Simulations

The second and the third types of thought experiments mentioned above consist in evaluating the consequences of theories, either to facilitate the design of real world experiments or to avoid actually carrying them out. Thanks to their simulation abilities, computers can play a similar role and they may anticipate the consequences of theories. What is more, computational simulations are far more accurate than mental experiments, because they can be quantified precisely and compared with empirical evidence. Therefore, they may help reduce considerably the number of real world experiments, which is desirable not only for economic reasons but also for ecological and ethical ones. This already happens in many domains; for instance, the testing of nuclear weapons has been greatly reduced thanks to computer simulations, and much progress has been made in the physics of materials, in climatology, in the environmental sciences etc., using computer models that anticipate natural phenomena.

Computational simulations integrate theories and we could say that the computational models on which simulations are based are theories. Thus, by specifying the input conditions and by running the simulation program, an experiment is performed in a virtual world that represents a theory with operations on symbols. It is clearly an *in silico* experiment.

All these simulations involve the transformation of representation and this last point needs to be underlined: *in silico* experiments presuppose some explicit and well-defined symbolic representation on which calculations operate. These symbols can be restricted to "sub-symbolic" features, i.e. numbers, but in all cases computations transform symbols that represent reality. In technical terms, symbolic representations rely on "ontologies" that associate inference mechanisms to sets of features. As they are only representations, these computational models are approximations of what they intend to represent. It follows that the goal of simulations is not necessarily to reduce reality to a calculation, but to anticipate some aspects of the reality through the use of a model.

Info-Computational Models

As said earlier, *in silico* experiments essentially encompass two principles, one which corresponds to an informational approach, i.e. to the evaluation of a hypothesis on prerecorded data, and the other to a computational view where theories are formalized and simulated using computers. Note that, as mentioned in (Dodig-Crnkovic 2007), two philosophical views, informationalism and computationalism, tend to favor reducing everything either to information, which is considered as the substance of the universe, or to calculations on which all changes, both physical and mental, are supposed to be based. This could mean that some *in silico* experiments resort to informationalism, others to computationalism, which would justify an info-computationalist synthesis as proposed by Gordana Dodig-Crnkovic (Dodig-Crnkovic, 2007). However, in the case of *in silico* experiments, both views are approximations. Databases do not contain exhaustive information on the world, but only a partial view of it, which means that hypotheses validated using informational experiments have to be confirmed. In the same way, digital models on which computer simulations are based are only partial approximations of reality (Noble, 2006); their scope is always restricted and there is no absolute world computer model. As a consequence, our goal is not to reduce epistemology, i.e. the theory of knowledge, to an informational view, to a computational perspective or to a combination of the two, but to see how computers in general, and *in silico* experiments in particular, modify the activity of scientists and the production of knowledge.

Computerized Epistemology

The CYBERNARD project

Epistemology has to take into consideration the way computers transform scientific activity and, in particular, experimental validation procedures. But epistemology may also be transformed by the use of computers in the reconstruction of old scientific discoveries. For example, work has been done on the rational reconstruction of old scientific discoveries using computers (Langley *et al*., 1987). However, this work does not really question the status of experimentation; most of it is based on past observations and tends to reduce scientific discovery to an inductive step. The goal of the CYBERNARD project is to understand Claude Bernard's experimental route (Ganascia & Debru, 2007) and to show that *in silico* experiments can reproduce the suggestions for experiments reported in Claude Bernard's notebooks. Before each suggested experiment, there are some conflicting hypotheses that need to be discriminated empirically. The simulation of these suggestions for experiments, under different theoretical hypotheses, shows the logical function of each of the planned experiments. It is then possible to see how theoretical investigations evolve with time. What this article claims is that such an attempt could profoundly modify methods in epistemology, since it makes it possible to reconstruct the representations scientists make in their everyday activities.

Core Models

To design a computational model that simulates the intellectual route leading Claude Bernard to his discovery, we have supposed that he had in mind what we call "core models" that contain basic physiological concepts – such as internal environment, organ names etc. – upon which he built his theories.

More precisely, Claude Bernard had in mind an ontology, which was explicitly described in his writings: he presumed that organisms are composed of organs, themselves analogous to organisms since each of them has its own aliments, poisons, stimulations, actions, etc. The internal environment, mainly the blood, carries organ poisons and aliments, while the actions of the organs may have different effects on other organs and, consequently, on the whole organism.

Theories correspond to hypothetical organ functions that Claude Bernard wanted to understand and explain, while "core models" describe the physical architecture of the organism reductions that were necessary for Claude Bernard's conceptualization. These "core models" constitute the core on which the reasoning process is based and, depending on the question under investigation, may be more or less simplified. For instance, if one wants to investigate the function of the heart, it is not necessary to detail the precise role of all muscles. The CYBERNARD project builds and simulates these "core models" using multi-agent architectures. Such simulations have to give a simplified view of Claude Bernard's representation of both the normal behavior of the organism and the consequences of a dysfunctioning organ due, for instance, to some toxic substance.

A second level of the model manages hypotheses relative to the function of different organs. Each working hypothesis is evaluated through empirical experiments. Claude Bernard assumed that one can use toxic substances as tools of investigation – he suggested the idea of a "chemical scalpel" – to dissociate and identify the functions of different organs. He presupposed, as an underlying principle, that each toxic substance neutralizes one organ at a time. When a toxic substance affects an organ, the anatomy of death shows how the organism behaves without the poisoned organ. Nevertheless, even when working on such a presupposition, many physiologists are puzzled by the investigation, because it is a double entry enigma: they have to understand and explain both the organ(s) contaminated by toxic substances and the function of the affected organ(s).

Our aim is to use "core models" to simulate all suggestions for experiments and to understand the place of these experiments in the discovery process using the hypothesis management module.

Towards an Electronic Epistemology

The description of *in silico* experiments given in this article shows how computers modify scientific activity and that, in a way, *in silico* experiments are instances of thought experiments. It is also argued that the criticisms leveled against thought experiments by philosophers, especially by Karl Popper, do not target *in silico* experiments. Although this point has not been fully dealt with here, it is certainly the role of contemporary epistemology to discuss such questions, because this concerns the present state of the sciences and the way knowledge is produced today. And as the description of the CYBERNARD project illustrates, the practice of epistemology may be transformed by the introduction of computer models.

To sum up, the extension of the place of computers in everyday life has an impact on epistemology, because the subjects studied and the methods used are changing. These changes are not only *in silico* and are not limited to reducing epistemology to an info-computational model. Modern epistemology is not condemned to become an abstract theory of knowledge and of how it is built, and may continue to consider the details of scientific activities, with concrete references to historical developments. To use another Latin phrase, this new computerized epistemology can be said to be *in situ*, since it is located in the concrete context of discoveries. To quote Gaston

Bachelard, "It will be a phenomenology of the studious man, of the man tense in his study and not only a vague assessment of general ideas and acquired results. It will have to make us attend the daily drama of daily study, to describe the rivalry and the cooperation of the theoretical effort and experimental research, to place us at the center of this perpetual conflict of methods, which is the manifest character, the tonic character of the contemporaneous cultural science.[1]"

However, this modern epistemology, which takes into account the influence of computers on daily scientific activity, is not restricted to the naturalization of epistemology, i.e. to the reduction of epistemology to a "science of nature". The cross-road between epistemology and computer science offers many alternatives. Some of them have been presented here, and they could be considered as anti-naturalizations. If we take the opposition between the "science of nature" and the "science of culture" that was introduced by the German philosopher Heinrich Rickert (1863-1936) we could say that computerized epistemology is not only a subject of the science of nature; it is also a science of culture, which shows and measures the influence of computers on the production of knowledge today.

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[1] « Elle sera une phénoménologie de l'homme studieux, de l'homme tendu dans son étude et non pas seulement un vague bilan d'idées générales et de résultats acquis. Elle aura à nous faire assister au drame quotidien de l'étude quotidienne, à décrire la rivalité et la coopération de l'effort théorique et de la recherche expérimentale, à nous mettre au centre de ce perpétuel conflit de méthodes qui est le caractère manifeste, le caractère tonique de la culture scientifique contemporaine. » Gaston Bachelard, « L'engagement rationaliste », Paris, PUF, 1972, p. 93

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