Archimedes 72 New Studies in the History and Philosophy of Science and Technology

Catherine Allamel-Raffin
Jean-Luc Gangloff
Yves Gingras *Editors*

# Experimentation in the Sciences

## Comparative and Long-Term Historical Research on Experimental Practice

Springer

# Archimedes

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*This book is dedicated to the memory of Ian Hacking (1936–2023), whose work brilliantly highlighted the crucial role of experimentation in science.*

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# Chapter 1
# The Characteristics and Diversity of Experimentation in the Sciences

**Catherine Allamel-Raffin, Jean-Luc Gangloff, and Yves Gingras**

This book is about experimentation in the sciences. It presents a panorama of the various ways of experimenting in both the natural sciences (physics, chemistry, biology, etc.) and the social and human sciences (psychology, economics, sociology, etc.) as well as in those of mixed or uncertain status such as medicine, management sciences and archaeology. More precisely, it provides reference points as to the nature, the concrete manifestations and the purposes of those activities designated as "experimentation". One might think that this book is the continuation of a long list of introductory works that approach the question of experimentation employing the expertise of the philosopher, the historian and the social scientist. There are, however, very few studies, apart from *Observation and Experiment in Natural and Social Sciences* (Galavotti 2004), that, in a single volume, cover the entire spectrum of experimental practices ranging from physics and chemistry to sociology, archaeology, psychology, economics and medicine. This absence can be explained by several factors including the fact that philosophers focus more on the natural sciences, and especially physics, than on the human and social sciences. In addition to this selective focus, much attention has been paid to assessing the validity of the results obtained to the detriment of the experimental methods themselves. There are, of course, some case studies, most often drawing on experiments considered classical or "crucial" in the history of science such as Galileo's inclined plane, Blaise Pascal's experiments on the weight of air conducted on the Puy-de-Dôme, or Pasteur and Pouchet's experiments on spontaneous generation.

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Going beyond these specific cases, the aim here is to think about the specificity of experimentation in the diversity of scientific practices concerning objects of very different nature. We will see consequently that the expression “scientific method” remains vague and acquires a precise operational meaning only with regard to the nature of the objects submitted to investigation. Thus, what do we know about the relative place accorded to experimentation, observation or simulation in various scientific practices? In what ways and in what capacity does experimentation provide evidence or proof with regard to objects as different as a star, a cell, an organ of the human body or a political riot? The answers to questions such as these will allow us, we believe, to identify the common basis of experimentation in the different sciences, while at the same time enable us to underscore the limits of a simplistic conception according to which there is only one way to provide proof, regardless of the particularities of the object under investigation. Since experimentation confers a stamp of scientificity, among other things, it is understandable that it is often the object of criticism and that those who believe that “science” is both unified and singular, also believe that experimentation is the same for all the “real” sciences. Though one can find examples of the experimental approach in Antiquity (Grmek 1997), it is fair to say that the experimental approach became systematic in the natural sciences during the seventeenth century and the humanities and social sciences have also come to invoke it, in addition to observation, to justify their status as science. What methodologies do these disciplines adopt? Is there continuity from one discipline to another? What about the “creation” of phenomena as it is common in physics or chemistry? Is such creation also at work in other disciplines such as medicine and the human and social sciences?

By experimentation, we mean a type of activity based on the voluntary, systematic and controlled modification of the conditions of the natural sequence of phenomena in order to determine which parameters contribute to producing a given effect (Dupouy 2011; Nadeau 1999; Soler 2019). More precisely, modification implies being able to: 1/ isolate variables, 2/ manipulate the variables, being able, in principle, to control each variable independently of all the others, 3/ reproduce their effects in order to determine which parameters contribute to producing a given effect. Reproduction ensures that the phenomenon is real, stable and not a simple artefact of the method, the instrument used or a poorly controlled environment. Experimentation is thus distinguished from observation, which is more passive and does not voluntarily disturb the observed phenomenon. As we will see, although the two types of scientific activity (observing and experimenting) are found in most of the sciences, contemporary disciplines are increasingly experimental and equipped with instruments. They are rarely only observational. And although one might perceive a continuity running between daily practice, or common sense experimentation and scientific experimentation, the first is generally less systematic, individual and sporadic and not committed to a collective argumentation, whereas the second is subject to the institutionalized rules of a scientific community. We are interested here only in the latter whose experiments are indeed subject to strong normative constraints linked to the collective character of institutionalized science. This normativity, inherent to scientific research, is present in the dynamics of argument and counterargument (Bachelard 1938; Bourdieu 2001; Gingras 2021). Debates among researchers concern, in particular, the conditions for the effective realization of experiments (manipulative skill, methodological rigor, etc.). They also concern the choices to be made regarding the characteristics of the relevant experimental devices. While the individual testing hypotheses at home is not confronted with other scientists who can contest it, the scientist is subject to the "norms that are expressed in the form of prescriptions, prohibitions, preferences and legitimated in terms of institutional values that will be internalized to varying degrees by the scientists" (Darmon and Matalon 1986, p. 209).

Under the influence of Pierre Duhem and Karl Popper, philosophy of science has long placed experimentation under the umbrella of theory. Even the constructivist and relativist sociology of science has often taken up Duhem's thesis and insisted on the fact that all experimentation or observation is necessarily linked to an underlying theory (theory-laden). Since the 1980s, however, a great deal of research has criticized this theory-oriented conception of scientific practice and highlighted the fact that observation and experimentation have a certain autonomy with respect to theories and that their purpose is not simply to test or refute them (Hacking 1983, 2004; Franklin 1986, 2016; Franklin and Perovic 2021; Karaca 2013). This relative autonomy of experimentation is not only logical, but also manifests itself at the level of social organization and the division of labor, notably in the form of the development of communities of experimenters (Galison 1987) and instrumentalist communities that work less on the phenomena than on the instruments used to produce or detect them (Joerges and Shinn 2001). Thus, a profound theoretical change can occur without any change in the experimental facts, or even in the experimental instruments and devices. Conversely, a major change in instrumentation can occur without the theoretical framework of the phenomenon studied being modified. This is what Thomas Nickles calls a disruptive change (such as the invention of the scanning tunneling microscope), the effects of which do not result in the formation of a new paradigm in the sense of Kuhn, but instead generate a new space of investigation (Nickles 2008).

The assertion, long presented as central to the philosophy of science, that experimentation and observation are intended only to test or disprove theories leads to a subordination of experimentation as a mere means, necessary but unproblematic in the context of logical analyses of scientific discovery. On the social level, this is reflected in the superiority conferred to theorists over experimenters, the latter rarely rendered visible in media accounts of scientific discovery. Once the relative autonomy of experimentation has been accepted, we can ask what other purposes can be attributed to experimentation within the framework of scientific investigation. Allan Franklin, for example, has noted that experimentation plays many other significant roles in science. These roles include "exploratory experiments designed to investigate a subject for which a theory does not exist so that a theory may be formulated; experiments that help to articulate an existing theory; experiments that call for a new theory either by demonstrating the existence of a new phenomenon in need of explanation or by demonstrating that an existing theory is wrong; experiments that provide evidence for entities involved in our theories or new entities; experiments that measure quantities that are of physical interest such as Planck's constant or the charge of the electron; and experiments that have a life of their own, independent of high-level theories" (Franklin 2016, pp. 1–2). Experimentation often requires instrumentation of varying sophistication, and one notable effect of these instruments is to stimulate the creation of new concepts (Gingras and Godin 1997, p. 152). Instruments also make it possible to create new phenomena, otherwise not directly observable or which do not (or rarely[1]) exist as such in nature, such as the Josephson effect, which manifests itself by the appearance of a current between two superconducting materials separated by a layer of non-superconducting insulating material (Hacking 1983, p. 228–229). Beyond the inevitable variations arising from the nature of objects, the essence of experimentation therefore lies first and foremost in the idea of *modifying* and *controlling* variables, and not in the idea of *confirming* or *refuting* a theory or a phenomenon. This idea appears notably in Claude Bernard's work when he proposes to distinguish between experimentation in the strict sense (the sense that interests us here) and experimental reasoning (or experimental method). For Bernard, "observation is the investigation of a natural phenomenon and experiment is the investigation of a phenomenon modified by the investigator" (Bernard 2008, p. 123). Experimental reasoning, as he defines it, is more encompassing and "is nothing other than reasoning by means of which we methodically submit our ideas to the experience of facts" (Bernard 2008, p. 103). It is therefore the same in the observational sciences as in the experimental sciences (*ibid.*, p. 125).

Although the conceptual distinction between observation and experimentation is essential, it does not imply the independent existence of "observational sciences" and "experimental sciences" Reality is more complex and most sciences use both observational and experimental methods. If astronomy is, for obvious reasons, mostly observational and nuclear physics experimental, chemistry almost always requires an intervention to combine substances, and biology in the broad sense is also, nowadays, more experimental than purely observational as it was at the time of early botany or zoology. Even archaeology, which one might imagine to be based solely on the more or less fortuitous discovery of artifacts (and therefore in this sense observational because it does not produce these artifacts), can also be experimental, as the chapter of this book dedicated to this discipline shows. The situation is also complex in most of the social sciences, which pursue actual scientific research and not simply social activism. The management sciences as well as economics, also claim to experiment and not just to observe. Through these few examples, the notion of modification appears to be the essential characteristic of scientific experimentation which is valid for all the objects investigated: atoms, molecules, stars, galaxies, living cells, individuals, social communities, etc. This characteristic feature of experimentation allows for a great diversity of practices linked to diverse contexts.

[1] Indeed, one cannot exclude rare natural occurrences such as what seems to have been, for example, the existence of a natural nuclear reactor in Gabon in a very particular geological context, more than two million years ago. See, Gauthier-Lafaye et al. (1997).

Thus, Ian Hacking has offered “a taxonomy of the internal elements of an experiment” and has identified fifteen items associated with scientific experimentation, which he has collected into three categories (Hacking 1992, pp.44–45). Within the category of “ideas”, he distinguishes:

- questions,
- background knowledge,
- high-level theories in relation to the subject, which have no direct experimental consequences,
- “topical hypotheses” (which make it possible to establish bridges between the high-level theories and experimentation),
- models related to the apparatus.

“Things” are divided into:

- the “target” (the substance or population studied)
- the source of modification (that which alters or interferes with the target)
- the detectors,
- the tools,
- the data generators.

Finally, with regards to “inscriptions”, Hacking discriminates between:

- the data,
- their assessment (statistical estimation of the probability of error, estimation of systematic errors due to the equipment),
- their reduction,
- their analysis,
- their interpretation.

For the informed reader, this taxonomy includes the usual items cited by philosophers of science influenced mainly by physics: “high-level theories”, “topical hypotheses”, “models related to the apparatus”, together with the distinction between “detectors” and “data generators” (which presupposes the existence of a complex and sophisticated instrumentation), not to mention the modalities of data processing. Nonetheless, it can be argued that while the list proposed by Hacking does identify the common elements of an ideal-typical definition of scientific experimentation, certain traits fade or disappear entirely depending on the discipline and specialty examined, as the contributions gathered here show. In addition, entirely new traits emerge that are not on Hacking’s list. In psychology, for example, an experiment includes complex data collection techniques, but it does not necessarily require the elaboration of topical hypotheses and does not necessarily use detectors, which are a source of multiple problems regarding the recording of data, etc. In contrast, social psychology uses control groups to guarantee the validity of the results obtained. Even within physics, some experiments do not contain all the items of the ideal-typical definition: in exploratory experimentation, for instance, we do not have high-level theory, since this type of experimentation aims precisely at constituting a new theory from the investigation of little-known phenomena.

Hacking himself insists on the item he designates as the "source of modification", which brings us back to the requirement of modification presented above as the only necessary and sufficient condition that any experiment must satisfy. In principle, the source of modification can itself take many different forms. But in keeping with his view of experimentation in physics as the prototype of experimentation in the laboratory sciences, Hacking writes:

> There is usually apparatus that in some way alters or interferes with the target. In certain branches of physics, this is most commonly a source of energy. Traditional inorganic chemical analysis modifies a target by adding measured amounts of various substances, and by distillation, precipitation, centrifuging, etc. (1992, p. 46)

In other words, it is a question of intervening on things by means of instruments. From this point of view, the sciences furthest from this conception of experimentation are the humanities and the social sciences. For this reason, one should not place too much emphasis on instruments to define experimentation and should rather stick to the idea of intervention. One can, for example, disrupt the behavior of a group of monkeys simply by unexpectedly throwing a bunch of bananas at them and observing their reactions! Although physics is in fact the science most heavily based on instruments, this does not by itself guarantee the "scientificity" of the experiment. One can indeed imagine multiple subtle and non-invasive means to modify mental states or individual or collective human behaviors. In social psychology, for example, one can manipulate the characteristics of the participants' social environment in various ways.

Depending on whether experimenters intervene on quarks or benzene or examine the behavior of credit buyers or an individual subjected to group pressure, the modalities of the intervention will change. Ways of investigating vary according to the objects of study, depending on their assumed or known ontological characteristics. As the contributions to this book show, it is *indeed the nature of the object under investigation that dictates the concrete modalities of the experiment* and it is the dynamics of the exchanges between the members of the community that validates the most robust methods that, in turn, allow researchers to produce knowledge specific to each discipline. We can easily surmise that the ethical consequences of experimentation are not the same for a protocol that aims to confine a set of atoms in a magnetic field to observe their behavior when subjected to various constraints and a social psychology protocol that confines humans to study their reactions to authority, as in the famous Milgram experiment (Milgram 2017). The same is true of the reproducibility issues that have surfaced in recent years, particularly in social psychology (Allison et al. 2016; Peterson 2021). It is easy to understand that if electrons are considered identical and indistinguishable from each other, the same cannot be said of human beings, for whom it is difficult to fully control all the variables and environments in which they live. Hence the need to adapt the experimental method to the specific nature of the objects studied.

In sum, beyond the positivist dream of a unified science, the diversity of objects in the world argues for a broader conception of scientificity based on a conception of experimentation adapted to the kind of objects studied: people and societies are not electrons or mices. This is what we believe the contributions gathered in this book show, covering a wide range of objects and experimental practices in a great diversity of disciplines, all aiming at producing valid scientific knowledge, but always subject to the critical scrutiny of the active members of these multiple scientific communities, a scrutiny that alone ensures the value of the knowledge produced thanks to ever more diversified and imaginative experiments.

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