DRAFT Please refer to: **Boon M. (May. 2015). The Scientific Use of Technological Instruments.** Chapter 4 in: *The Role of Technology in Science: Philosophical Perspectives*, S.O. Hansson (ed.). Dordrecht: Springer Series: Philosophy of Engineering and Technology 18, DOI 10.1007/978-94-017-9762-7_4.
http://www.springer.com/philosophy/epistemology+and+philosophy+of+science/book/978-94-017-9761-0

The Scientific Use of Technological Instruments

MIEKE BOON
Department of Philosophy, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands m.boon@utwente.nl

Abstract

One of the most obvious ways in which the natural sciences depend on technology is through the use of instruments. This chapter presents a philosophical analysis of the role of technological instruments in science. Two roles of technological instruments in scientific practices are distinguished: their role in discovering and proving scientific theories, and their role in generating and investigating new physical phenomena that are of technological relevance. Most of the philosophy of science is theory-oriented and therefore tends to ignore the importance of producing and investigating physical phenomena in current scientific practices. This chapter selectively chooses some recent trends in the philosophy of science that relate to the role of technological instruments in order to indicate the potential for philosophical accounts of scientific practices that productively integrate the two roles of technological instruments.

Keywords: technological instruments, phenomena, scientific practice, New Experimentalism, measurement.

1. Introduction

At present, many accept that modern science and technology are interwoven into a complex that is sometimes called 'technoscience'.[1] When focussing on how technology has an effect on scientific practices, two roles can be distinguished. On the one hand, much of the progress of science is driven by the sophistication of instrumentation. Conversely, scientific research plays a crucial role in the development of *high-tech* devices. Related to these two roles of technology in science, two functions of technological instruments can be distinguished: Firstly, as experimental equipment and measuring devices, which have an *epistemological* function in developing and testing scientific theories and models. Secondly, technological devices play a *material* role in the production of specific physical phenomena, in particular those that may be of interest for performing a technological function.

This is exemplified by a simple historical example such as Robert Hooke's experimental set-up in which the elasticity of a spring was studied. On the one hand, the experimental set-up of springs and weights and measurements of lengths has an epistemological function in finding laws that describe this phenomenon, such as Hooke's law. At the same time, the physical phenomenon – the elasticity of a device or material – is utilized in technological applications. Scientific research in this application context aims, for instance, at an understanding of the elastic behaviour such that it can be produced or manipulated in specific objects, materials or devices. Another example is superconductivity in mercury at temperatures near absolute zero, which is a phenomenon that on the one hand calls for a scientific explanation, while on the

[1] The focus of this article will be on techno-science in the narrow sense, namely, how experimentation and instrumentation in scientific practices is entangled with the development of technological instruments – which, on the one hand, have a role to play in scientific practices, but on the other hand, will be developed further into concrete technological devices outside the laboratory. A focus on experimentation and instrumentation as the crucial link between science and technology draws attention to materiality, such as technologically relevant physical phenomena, which are produced through experimentation and instrumentation. Conversely, most of the traditional philosophy of science focuses on theories as the major aim of science. Techno-science as a movement addresses much broader issues, which are not commonly addressed in the philosophy of science but which are part of the philosophy of technology (see, for instance, Idhe and Selinger 2003, and Radder 2004).

Alfred Nordmann (2012) presents a description of 'techno-scientific knowledge' similar to what I aim to say about the aim of scientific research from a 'phenomenon-oriented' (rather than 'theory-oriented') perspective on the role of technological instruments in scientific research: "Techno-scientific knowledge includes the acquisition and demonstration of basic capabilities. … Rather than being applied science or applied techno-science, then, there is basic techno-scientific research which consists of demonstrated capabilities to visualize, to characterize substances, to measure and model – and, of course, to manipulate and control surprising phenomena" (Nordmann 2012, 19), also see Lacey (2012).

Also see Boon (2011) in which I present an overview of the literature on the relationships between science and technology, and an analysis of their epistemological relationship.

other hand the technological significance of this phenomenon calls for scientific research that demonstrates how this phenomenon can be produced or manipulated under different conditions and in different materials. Some scientific research projects, for instance, are dedicated to the development of ceramic materials that are superconductive at higher temperatures, a feature which is crucial for viable technological applications.

These two roles of technological instruments in science can be captured in terms of two distinct philosophical perspectives on modern scientific research. Firstly, the traditional view of the philosophy of science in which the focus is on the theories. From this perspective, the primary aim of science is the discovery and justification of theories, for which the development of technological instruments is subservient. The alternative perspective considers scientific research in application contexts. Broadly speaking, it focusses on the technological production and measurement of physical phenomena significant to technological applications in the broad sense, which includes technology in the narrow sense, but also medicine and agriculture, and all kinds of measurement techniques. In this alternative view, scientific research firstly aims at the material production and theoretical understanding, both of relevant phenomena as well as the technological instruments that create them. This presumes the simultaneous material and theoretical development of (1) relevant physical phenomena and the technological instruments that produce them, as well as (2) scientific knowledge that may be used to describe or explain both the phenomenon and the workings of the technological instruments – where 'scientific knowledge' includes empirical knowledge, theoretical concepts, scientific models, etc. Below, I will refer to these two perspectives on science as 'theory-oriented' and 'phenomena-oriented'.

The 'theory-oriented' perspective has been dominant in traditional philosophy of science. In most of that tradition, the role of technological instruments has been neglected. Only in the last few decades has progress been made towards a philosophical understanding of the epistemological roles of instruments and experiments in the justification of scientific theories. This chapter aims to give an overview of this important movement in the philosophy of science.[2]

[2] Authors such as Don Ihde (1991, 2009), Hans Radder (1996, 2003a), Davis Baird (2003, 2004), Joe Pitt (2000) and several others have been pioneering in attempts to build a bridge between the philosophy of science and the philosophy of technology by emphasizing the epistemic and material role of instruments in scientific practices, and trying to steer away from a theory-oriented perspective on science. Although I acknowledge the significance of their contributions, I will focus on developments towards such insights within 'main stream' philosophy of science.

The structure of this chapter is as follows: Section 2 will sketch the philosophical background against which interest in the role of technological instruments in science emerged. Sections 4-6 present an outline of so-called *New Experimentalism* and other trends in the philosophy of science that address the role of experiments and technological instruments in scientific research, focussing on: (1) philosophical accounts of their roles in the justification of scientific theories, and (2) taxonomies and epistemologies of instruments and experiments. These topics will be presented within the 'theory-oriented' perspective from which science tackles the discovery and justification of theories. But it will become clear along the way that these topics are also relevant to a better understanding of the second aim of modern science, namely, the invention of 'high-tech' things – such as instruments, materials, and apparatus – which relies on a scientific understanding of phenomena that are technologically produced and the sophisticated instruments used in their creation. In Section 7, it will be argued that a full-grown philosophical account of this second, epistemic and material role of technological instruments in scientific research is still lacking. Nonetheless, the New Experimentalist movement, together with some recent work in the philosophy of science that explains *how* the development of technological instruments and the formation of theoretical concepts are crucially entangled, give directions towards a more viable understanding of both the character of scientific knowledge and of how scientific research contributes to the development of high-tech devices – on this track, the two perspectives merge in a productive manner.

2. Positivistic Philosophy of Science

In a traditional positivistic view, the aim of science is the production of reliable, adequate and/or true knowledge about the world. Positivistic philosophy of science thus focuses on theories produced in science. Its task is to produce accounts of confirmation and inductive inference that justify these theories. It assumes that the role of instruments and experiments is for testing hypotheses in controlled laboratory settings, and as such the instrumentation and experimentation are mere data providers for the evaluation of theories. Positivists do not make a distinction between observation through our senses and observation by means of instruments in experiments. Instruments are *instrumental* to the articulation and justification of scientific knowledge of the world. Although not doing full justice to the positivists view, the implicitly held metaphor is that scientists observe nature through technological spectacles that are not thought to significantly influence the resulting picture of nature (also see Rouse 1987[3]). As a consequence, the ways in which pictures and data are produced and evaluated by means of instruments and experiments has not been a topic of much concern to positivistic philosophy of science.

A classical problem for the positivistic idea of testing theories is the Duhem-Quine problem of under-determination of theories by empirical evidence. If an experiment or observation is persistently inconsistent with theory, one could either revise the theory, or revise the auxiliary hypotheses – for instance those that relate to the proper functioning of the instruments. An additional severe attack to the positivistic image of science came from Popper (1959, p. 156), who claims that all observation is theory-laden. To him, observations, and even more so observation statements and statements of experimental results, are always interpretations of the facts observed; they are *interpretations in the light of theories* (also see Van Fraassen 2012). Kuhn's notion of paradigms was conceived in a similar vein: rather than observation, the paradigm is basic, and observations only exist insofar as they emerge within the paradigm.

Since non-empirical factors seem to dominate the experimental work from its initial planning to its final result, the philosophical idea that theories are tested in experiments has become problematic. This is a severe threat to philosophical justification of the empirical and logical methodology of testing scientific theories proposed in logical positivism and empiricism. Signifying and addressing these threats has been very influential because it opened the road to extreme sceptical appraisals of science.

Recent approaches in the philosophy of science have changed focus from the logic of justification of scientific theories to the role of experiments and instruments in scientific reasoning. These new approaches can be understood as an attempt to solve two problems simultaneously. On the one hand, they aim to shed light on the problem of whether science can test theories if experimental results involve theoretical interpretations. On the other hand, they

[3] According to Rouse (1987): One might say that the traditional philosophical model of the local site of research is the observatory. Scientists look out at the world to bring parts of it inside to observe them. Whatever manipulative activities they perform either are directed at their instruments or are attempts to *re*produce phenomena in a location and setting where they will be observable. The new empiricism leads us instead to take seriously the *labor*atory. Scientists produce phenomena: many of the things they study are not 'natural' events but are very much the result of artifice (Rouse 1987, 23).

aim at resisting the scepticism that resulted from embracing the theses of under-determination of theory by evidence and the theory-ladeness of observation. They suggest, instead, that understanding the problems of under-determination and theory-ladeness involves understanding the role of experiments and instruments in testing scientific theories. Philosophical issues raised by these recent approaches include: How can experimental results be justified, that is, how do we know whether we observe a natural phenomenon or rather an artifact of the experimental set-up. How do we know that the instrument is functioning properly? Can we observe nature by means of our instruments without influencing the resulting picture of nature if the design of these instruments involves theoretical considerations? Can we make an ontological distinction between *Nature* and instrument anyway? Do theories confirmed in the laboratory apply to the world outside, and how can we generalize experimental results if at all? These are the kind of questions that are of interest to the so-called *New Experimentalists*.

3. New Experimentalism

Robert Ackermann gave the name of *New Experimentalism* to philosophical discussions that focused on the role of experiments and instruments in science, and which therefore, attempted to overcome the draw-backs of logical empiricism, and so avoid the scepticism of the social constructivists (Ackermann 1985, 1989; also see Mayo 1994). Some of the key figures of this movement from the 1980s and early 1990s included Ian Hacking, Nancy Cartwright, Allan Franklin, Peter Galison, Ronald Giere, Robert Ackermann himself, and more recently, Deborah Mayo.

Although each of these authors has a different focus, they share several viewpoints on the course of philosophy of science. They defend a philosophy that considers scientific practices, and they do not accept the restriction to the logic of science that positivistic philosophers had set for themselves. Traditional philosophical accounts of how observation provides an objective basis for evaluation of theories by the use of confirmation theory, or inductive logic, should be replaced by accounts of science that reflect how experimental knowledge is actually arrived at and how this knowledge functions. Obviously, the traditional distinction between the context of discovery and the context of justification, which motivated philosophers to restrict their task to the logic of justification of scientific theories, is abandoned. Instead, the New Experimentalists aim at an account of the rationality of scientists in scientific practices that includes how scientists reason about experiments, instruments, data, and theoretical knowledge.

Philosophical progress in this new tradition leans heavily on historical case studies that focus on aspects of experiments and instruments. These historically informed approaches strengthen the tradition that may have been ushered in by Thomas Kuhn, and which is now called the 'history and philosophy of science'. Reliance on historical case studies does not necessarily open the door to sociologically flavoured explanations of science, since an additional viewpoint shared by the New Experimentalists is that abstracting from sociological aspects of scientific practices, i.e. focussing on elements internal to scientific practice, is justified. Thus, the focus is on epistemological aspects of experiments, instruments, data and the processing of data, and different layers of theorizing, rather than the relationships between scientists, instrument builders, laboratories, editors, journalists, industry, government, media, and the public, which are important to social studies of science. Although, these philosophers admit that sociological and contingent factors may determine the course of science, they deny that sociological factors are determining methodological and epistemological criteria internal to scientific practices.

In general, the New Experimentalists share the view that focusing on aspects of experiments and instruments holds the key to avoiding or solving a number of problems, such as the under-determination of theory by empirical knowledge, the theory-ladeness of observation, and extreme sceptical positions – such as social constructivist – that result from it. In their view, these problems stem from the theory-dominated perspective on science of positivistic philosophers of science.

4. Theory-ladeness of Observation

i. 'Experiments have a Life of their Own'.

In 1913 the Dutch physicist Heike Kamerlingh Onnes was able to achieve in his experiments temperatures near to absolute zero, and he discovered that mercury became superconductive under these circumstances. It took to 1957 before Bardeen, Cooper, and Schrieffer put forward a theoretical explanation of this phenomenon - the BCS theory. These kinds of discoveries of new phenomena can be taken as counter-examples to Popper's claim that observation in an experiment is always a theoretical interpretation of the facts observed. Some phenomena are observed for which there is no theory. The discovery of superconductivity resulted from studying the behaviour of metals at temperatures near absolute zero. This discovery was independent of the theory that later explained the phenomenon. In scientific practice, some experiments produce reproducible phenomena – often called 'phenomenological laws' – that await a theoretical explanation. Therefore, observations of experimentally produced phenomena such as superconductivity, are not always theory-laden in a problematic sense.

Ian Hacking (1983) used these kinds of historical cases of discoveries of new phenomena to argue that 'experiments have a life of their own', meaning experiments have more objectives than the mere aim of *testing* theories (also see: Galison 1987, 1997; Steinle 2002, 2006; Radder 2003, and Franklin 2005). Hacking gives several other examples in which observations of phenomena were possible before there was any theory to explain them. The shift of emphasis on the role of experiments for testing theories to their role in producing reproducible phenomena, as indicated by Hacking, also indicates a shift of focus in the philosophy of science regarding the aim of science.

The important contribution of the discovery of superconductivity was not that it confirmed a theory about the world, but the discovery of that phenomenon, *i.e.* that such a phenomenon exists (it is worth keeping in mind that this phenomenon is not naturally occurring, but technologically produced). Furthermore, aiming at a theoretical understanding of this phenomenon and of the materials and physical conditions that produce it is not just driven by scientific curiosity, but also by the goal of technologically producing and utilizing this physical phenomenon.

ii. 'Data' versus 'Meaning of Data'.

In a strict positivistic view, one could refuse to acknowledge that *observing* superconductivity of metals near absolute zero involves theories of the instruments that are used for measuring the conductivity of the metal. This is one of the topics addressed by Ackermann (1985). He agrees that *data* given by instruments – such as data produced by a conductivity meter – may be given independent of theory. Instruments create an invariant relationship between their operations and the world, at least when we abstract from the expertise involved in their correct use. These readings are also independent of changes in the theory. An instrument reads 2 when exposed to some phenomenon. After a change in theory, it will continue to show the same reading, but we may take the reading to be no longer important, or, to tell us something other than what we thought originally. Thus, the *meanings of data* – such as superconductivity – are not given by the data, since the data are interpreted as such and such phenomenon through the use of theories. Without a theory and theoretical expectations, some data may not even be noticed. In addition, data may be interpreted differently by different theories (also see Van Fraassen 2012). When our theories change, we may conceive of the significance of the instrument and the world with which it is interacting differently, and the datum of an instrument may change in significance, but the data can nonetheless stay the same, and will typically be expected to do so. However, according to Ackermann, although data have an internal stability, which is reproducible through the use of instruments, their meaning is neither manifest nor stable.

Also other authors have criticized the idea that observations by means of instrument are independent of theory. Hacking's (1983) idea has been criticized for having a positivistic stance towards experiments very similar to Logical Empiricism (e.g., Carrier 1998). Others have argued that experiments often do not reveal actual states of affairs. In exploratory experiments it requires the formation of new basic concepts – such as the notion of a current circuit in the case of Ampère – before the data produced by the instrument can be interpreted as a phenomenon (e.g., Harré 1998, Steinle 2002, 2006).

One of the issues at stake is how new theoretical concepts (such as super-conductivity) are formed in cases such as the experiments by Kamerling Onnes. Since Popper (1959), and Kuhn (1961, 1970), a common reply in the philosophy of science has been that the formation of new theoretical concepts on the basis of experimental observation involves the theory that is supposed to be tested or discovered by these observations (i.e., the problem of the theory-ladeness of observation). Traditionally this entanglement of theories and observation was considered problematic as it threatens the objectivity of science.

In Section 7, a brief outline will be given of how studies of the roles of experimentation and instrumentation initiated by New Experimentalists have continued. These have provided more refined insights and distinctions that allow for moving away from foundationalist desires concerning the justification of theories, while at the same time avoiding sceptical conclusions.

In particular, recent approaches in the philosophy of science suggest that the formation of new *theoretical concepts* for interpreting experimental observations – such as those made by

Kamerling Onnes – are entangled with the *formation* of theories, on the one side, and the development of instruments and experiments, on the other, in a process called 'triangulation' (also see below, Hacking 1992). I will argue that these enriched accounts of the relationship between theories and experimental observations agree with the 'phenomena-oriented' perspective on the role of technological instruments in scientific research. This opens the way for a philosophy of science that explains how scientific research contributes to the development of technological devices.

iii. 'Representing' versus 'Intervening'.

An important claim by Hacking (1983) is that much of our empirical knowledge does not result from passive observation by means of instruments, but from *interventions* with instruments. The spectacle metaphor of instruments is replaced by a metaphor where the instruments become a material playground that provides us with a way to learn a lot about the world and about phenomena produced by these instruments. Observation as a source of empirical knowledge is extended to include *doing*, by *interacting* and *intervening* with the world through our instruments. Only by intervening do we discover the material resistances of the world. This source of empirical knowledge provides additional constraints that may overcome the problem of under-determination of theory by observation (also see Section 5.i).

Hacking's emphasis on the role of intervention is an important step towards an orientation on the role of phenomena in scientific research. By interacting and intervening with technological instruments, scientists firstly produce (new) phenomena. As has been indicated in the former section, a phenomenon is established through the entangled activities of materially producing it and forming a theoretical concept. Next, scientists aim to reproduce or manipulate the phenomenon through interventions with instruments and experimental set-ups, which enable investigation, but at the same time generate and shape the phenomenon.

Following up on Hacking's notion, it will be argued (in Section 7) that according to a phenomenon-oriented perspective, instead of accurate representations of the world as it is being the aim of scientific research, the researchers, often try to understand the results of active interventions with the world by means of technological instruments.

5. Underdetermination of Theory by Empirical Data

i. The Self-vindication of the Laboratory Sciences

One way to avoid the Duhem-Quine problem of underdetermination has been proposed by Hacking (1992). He claims that our preserved theories and the world fit together, not solely because we have found out how the world is, but rather we have tailored each to the other. As laboratory science matures, it develops a body of types of theory and types of apparatus and types of analysis of data that are mutually adjusted to each other. Any test of theory is related to apparatus that has evolved in conjunction with it - and in conjunction with modes of data analysis. Conversely, the criteria for the working of the apparatus and for the correctness of analyses are precisely the fit with theory. Hence, phenomena are not described directly by Newtonian concepts. It is rather certain measurements of the phenomena – generated by a certain class of what might be called 'Newtonian instruments' – that mesh with Newtonian concepts. The accuracy of the mechanics and the accuracy of the instruments are correlative. This process of tailoring the elements of experiments to fit together is what Hacking calls the self-vindication of laboratory science.

To explain this idea, Hacking proposed a taxonomy of experiments, which consists of fifteen elements internal to the experiments. This list of elements is divided into three groups, which are: (1) the intellectual components of an experiment ('ideas'), such as systematic theories, background knowledge, theoretical models of the apparatus, phenomenological laws, and hypothesis; (2) the material substance that we investigate or with which we investigate ('things'), such as the apparatus, the tools and instruments, the substances, and the material objects investigated; and (3) the outcomes of an experiment and the subsequent manipulation of data, such as data-reduction, calculations that produce more data, and interpretations ('marks').

Contrary to the Duhem-Quine thesis that theory is underdetermined by data, Hacking argues that the constraints of these fifteen elements allow too few degrees of freedom. All the elements can be modified, but when each one is adjusted with the others so that our data, our machines, and our thoughts cohere, interfering with any one throws all the others out of kilter. It is extraordinarily difficult to make one coherent account, and it is perhaps beyond our powers to make several (Hacking 1992, 55).

Next, Hacking argues for a new conception of how theories are tested in experiments. This conception disagrees with positivistic ideas of testing theories. Theories are not checked by comparison with a passive world with which we hope they correspond, but with a world in which we intervene. We do not formulate conjectures and then just look to see if they are true. Instead, according to Hacking, we invent devices that produce data and isolate or create phenomena, and a network of different levels of theory is true to these phenomena. Conversely, we may in the end count them as phenomena only when the data can be interpreted by theory. Thus there evolves a curious tailor-made fit between our ideas, our technological instruments, and our observations, which Hacking calls a coherence theory of thought, action, material things, and marks.

In this approach, Hacking shows another way of dealing with the problems of the theory-ladeness of observation, the under-determination of theory by empirical data, and the scepticism to which this could lead. Instead of showing – by means of case-studies – that many exceptions to these problems can be found in scientific practice, and thus, that the philosophical problems have been exaggerated, he now accepts that theories, things and data are mutually adapted in order to create mutual coherence.

ii. Epistemology of Experiments and Instruments

Allan Franklin (1986, 2002, 2005) addresses the question of how experimental results can be justified, that is, how we know that the instrument is functioning properly, and how we know whether we observe a natural phenomenon or a mere artefact of the instrument. In examining this problem he carried out detailed case studies of experiments in physics, and reconstructed how scientists reasoned about their results. From this analysis, he proposes a number of epistemological strategies that scientists regularly use, such as: observation of the same phenomena with different pieces of apparatus; prediction of what will be observed under specified circumstances; examination of regularities and properties of the phenomena themselves which suggest they are not artefacts; explanation of observations with an existing accepted theory of the phenomena; the elimination of all sources of error and alternative explanations of the results; evidence to show that there was no plausible malfunction of the instruments or background that would explain the observations; calibration and experimental checks; predictions of a lack of phenomena; and statistical validation. According to Franklin, in assessing their results, scientists act rationally when establishing the validity of an experimental result or observation on the basis of such strategies. He calls his articulation of the strategies of scientists who aim at validation of observation an *epistemology of experiment*. What is new in Franklin's approach to scientific reasoning is the crucial role played by 'errors'. In the validation of observations by means of instruments, he suggests, scientists focus on all possible sources of errors.

iii. Error and the Growth of Experimental Knowledge: Learning from Error

Deborah Mayo (1996) is another author, who, in an attempt to explain how scientists approach the problem of reliable knowledge, emphasises the importance of learning from errors.

How do scientists know that empirical data provide a good test of, or reliable evidence for a scientific hypothesis? In a traditional approach, philosophers seek the answer in the logical relationship between evidence and hypotheses, producing theories of evidence, confirmation, and inductive inference. In contrast, Mayo claims that answering this question requires an account for what happens in the production of evidence in scientific practice. This calls for an analysis of how scientists acquire experimental knowledge, that is, of how the data were generated in specific experimental testing contexts.

In her view, scientists do not focus on evidence for their hypotheses. Instead, much of the effort is concentrated on the reduction of errors. This is done by articulating and testing alternative hypotheses, and by tracking down sources of errors in instruments and experiments. One of her core ideas is that scientists come up with hypotheses at many different epistemological levels of scientific experimentation, and put these hypotheses to *severe tests*. Thus, it is not the highbrow scientific hypothesis that philosophers are usually interested in that are put to test in the first place, but hypotheses about the proper functioning of instruments, hypotheses about the proper functioning of the object under study (e.g. does it require shielding to external influences), and hypotheses about the rightness of data that are usually inexact and 'noisy'. It is important to notice that this includes hypotheses on possible errors in the functioning of instruments and the system under study, and errors in the data produced. These hypotheses involve 'intermediate' theories of data, instruments, and experiment. It is in this manner that scientists track down errors, and correct data and make adaptations to the instruments and experimental set-up.

Mayo's key idea for specifying the character of 'severe tests of hypotheses' is the application of statistical tests. The severity of a test to which a hypothesis *h* is put, is related to the probability that a test would reject *h* if *h* were false. For instance, a test is a severe test of hypothesis *h* if *h* implies observation O, and there is a very low probability of observing O if *h* is false. In her view, the method of statistical tests is a means of learning. On this account, one learns through scientific inquiry, not from how much the evidence confirms the hypothesis tested, but rather from *discordant* evidence and from finding anomalies. Hence, scientists learn from 'error' and error correction, which is an important extension to Hacking's idea that they learn from *intervention*. Mayo's account shows how low-level testing works, and how this method of identifying sources and magnitudes of error, serves in testing higher-level theory. She thus shows that a piecemeal, 'bottom-up' analysis of how scientists acquire experimental knowledge yields important insights into how science works (Mayo 1996, 2000; also see Hon 1998 and Carrier 2001).

6. Theory-ladeness of Instruments

i. Do we see through a Microscope?

Additional to the problem of theory-ladeness of observation, there is the problem of whether we can observe nature by means of our instruments if the design of these instruments involves theoretical considerations. Several authors have given their support to the idea that the theory-ladeness problem of instruments can be excluded, at least in some of our observations with instruments (e.g., Baird 2003, 2004, Heidelberger 2003, Lange 2003, Rothbart 2003, see Section 6.iv). A favoured example is observations by means of microscopes and other instruments with which objects can be made visible (e.g. Hacking 1983, Chalmers 2003).

Common ideas about the possibility of avoiding the problem that observations by means of instruments are theory-laden, and therefore not objective, are reminiscent of a Lockean kind of empiricism, which supposes that a distinction can be made between primary and secondary properties. Primary properties (or features) of things are 'out there', in the world, while secondary properties are 'in us', in our minds. In Locke’s time most measurement instruments that we know of today, did not exist. Therefore, the only primary properties of objects were: extension in space, shape, motion, number, and solidity (or impenetrability). These primary properties had the 'power' to cause *in us* not only perceptions of shape, motion, etc., but also perceptions of secondary properties, such as colour, sound, warmth or cold, odour, etc. These latter perceptions did not 'correspond' to the primary properties of material objects.

Nowadays, many properties can be ‘observed’ by means of instruments and specific measurement procedures. Therefore, the list of supposed primary properties can be extended to include those that are measured; for instance, temperature, wave-length, electrical resistance, and magnetic field strength (also see the properties listed in *The Handbook of Chemistry and Physics*). The challenging question is how to understand the role of instruments in the measurement of these properties. Can they be called ‘primary properties? Or, differently put, in what sense do measurements by means of instruments *represent* properties of the world ‘out there’?

ii. Theory-ladeness of Measurements

The epistemological ideal in the measurement of properties by means of instruments is technologically aided ‘comparison’ or ‘observations,’ or a combination of both. Metaphorically speaking, the epistemic contribution of a measuring instrument is similar, either to the use of an external standard such as the meter, or to the use of an instrument that enhances the senses such as a microscope or telescope. By means of these instruments certain properties or behaviours of the experimental set-up are ‘compared’ with a standard, or ‘observed’. Ideally, the measured property or the phenomenon is isolated and quantified by the measuring instrument, but not in any significant sense physically or conceptually affected by it, let alone, produced by it.[4]

Hasok Chang (2004) who performed a detailed historical study into one of the most 'taken for granted' instruments of scientific practice – thermometers – has, however, challenged this idea. The development and testing of thermometers was radically different to the

[4] Frigerio *et.al.* (2010) present a clear outline of this so-called representational theory of measurement, which holds that to measure is to construct a representation of an empirical relational system to a numerical relational system, under the hypothesis that relations in the empirical relational system are somehow observable (Frigerio et. al. 2010, 125). The crucial question regarding the theory-ladeness of measurement is to what extent the construction of a representation involves theory.

development of microscopes and telescopes, since the measurement of temperature lacked a solid reference. This led to an unavoidable circularity in the methodology of testing in thermometry. Scientists had to consider: How they could test whether the fluid in their thermometer expands regularly with increasing temperature without a circular reliance on the temperature-readings provided by the temperature itself. And, how they, without having established thermometers, could find out whether water boiled or ice melted always at the same temperature, so that those phenomena could be used as 'fixed points' for calibrating thermometers. Chang shows that the route to thermometers that gave correct temperature readings was long, and intellectually and experimentally challenging.

Although the so-called representational theory of measurement (e.g., Krantz et al. 1971, Suppes et al. 1990, Luce et al. 1990) assumes that theory-ladeness is not overly problematic to observations by means of measurement instruments, Chang shows that stabilizing observations by means of instruments involves many indispensable theoretical considerations. He arrives at a conclusion that is more constructivist than Hacking (1992) who takes as a basic idea that the material world warrants the objectivity of scientific knowledge and also, that empirical knowledge of the material world does not rely on our theories of it (also see Chang 2009b). In Chang's view, through philosophers' attempts to justify measurement methods we discover that circularity is inherent. His example of thermometry shows that finding empirical knowledge of temperature involved theoretical assumptions about the properties of matter and heat.

The basic problem for a philosophical account of empirical science is that it requires observations based on theories, whereas empiricist philosophy demands that those theories should be justified by observations. Chang holds that the only productive way of dealing with that circularity is to accept it and admit that justification in empirical science has to be *coherentist* instead of foundationalist. Within such coherentism, *epistemic iteration* provides an effective method of scientific progress, since it involves simultaneous corrections of interrelated theory (such as thermodynamics) and instruments (such as thermometers), which results in stable systems (also see Hacking 1992).

iii. Nomological Machines

An important aspect revealed by Chang's analysis of the history of thermometry is the epistemic and technological efforts needed for constructing a stable technological device. It shows the entanglement of building a stable technological device (e.g., a thermometer), with 'stabilizing' empirical knowledge (e.g., that water boils at 100 ^{0}C), and producing theoretical knowledge (e.g., laws of thermodynamics). Understanding how a stable technological device is produced is relevant for a different take on a question such as: how the generalization of experimental results is justified, and why theories confirmed in the laboratory apply to the world outside. Returning to the musings of Hacking (1992), it will be argued in Section 7 that the stabilization of instruments such as described by Chang, is crucial for the stabilization and applicability of scientific knowledge.

Nancy Cartwright (1983, 1989, 1999) is one of the first authors who stressed the role of instruments in 'discovering' laws of nature. She holds that in the positivistic tradition, theoretical laws that are tested in experiments are conceived as necessary regular associations between properties. However, according to Cartwright, in order to test these laws we create so-called *nomological machines*. A nomological machine is a fixed arrangement of components, or factors, with stable capacities that in the right sort of stable environment will give rise to regular behaviour. Laws represent this regular behaviour of nomological machines, which implies that those laws hold as a consequence of the repeated, successful operation of nomological machines. Therefore, laws – understood as a necessary regular association between properties – do not necessarily hold for the world beyond the nomological machine, which also means that laws do not necessarily exist as independent entities in nature. In the vocabulary of this chapter, the physical phenomenon produced by the technological instrument may not exist independent of (crucial aspects of) the instrument.

On the basis of her analysis of the role of nomological machines in science, Cartwright rejects the view that is held by many philosophers of science, that laws are basic to our scientific knowledge, and that other things happen on account of them. In Cartwright's view, *capacities* are basic, and things happen on the account of capacities that are exerted in particular physical circumstances. Laws arise following the repeated operation of a system of components with stable capacities in particular fortunate circumstances. Therefore, according to Cartwright, our most wide-ranging scientific knowledge is not knowledge of laws but knowledge of the natures of things, which includes knowledge that allows us to build new nomological machines, or, in my vocabulary: technological instruments that produce a specific physical phenomenon such as elastic or superconductive behaviour.

The views presented so far, allow for a shift to the second philosophical perspective (developed in Section 7), which assumes that scientific research also aims at the production and theoretical understanding both of physical phenomena and of the instruments creating them. Hacking's (1992) taxonomy of experiments proposes that scientific practice produces (1) instruments, (2) theoretical knowledge that interprets the working of these instruments and explains how these instruments bring about a phenomenon of interest, and (3) theoretical knowledge of how data produced by these instruments need to be interpreted and processed. Yet, Hacking's account does not explain how scientific knowledge can travel beyond the coherent structure in which it has emerged. Cartwright's account, on the other hand, indicates that we acquire knowledge of the physical and instrumental conditions at which certain capacities will exert themselves, which explains how we are able to theoretically predict and interpret the working of instruments and phenomena at new circumstances.

iv. Other Types of Theory-ladeness of Instruments

Radder (2003a) has edited a collection that explicitly focuses on the role of technological instruments in scientific experiments. One of its topics is the characterization of different types of theory-ladeness of observation by means of instruments (e.g. Baird 2003, Heidelberger 2003, Hon 2003, Lange 2003, Radder 2003, Rothbart 2003). Heidelberger agrees with Kuhn that any observation is coloured through a paradigm, that is, through the cognitive background that is required to make an observation. Nonetheless, Baird, Hon, Heidelberger, Lange and Rothbart agree on the idea that a distinction can be made between the theoretical understanding of instruments that produce, construct or imitate phenomena, which is an understanding at the causal, phenomenological or instrumental level, and the theoretical interpretation of the observations made by means of these instruments.

However, the idea that a distinction is possible between the theoretical understanding of instruments and the theoretical interpretation of observations made by means of these instruments, may be less straightforward than these authors suggest. Their view involves a commonly accepted idea, which is well expressed in Radder's definition of experiment: "An experimenter tries to realize an interaction between an object and some apparatus in such a way that a stable correlation between some features of the object and some features of the apparatus will be produced" (Radder 2003, 153). This definition assumes a clear distinction between the object and the apparatus: But what about the role of the *interaction* between the two? Does not this interaction *produce* a physical phenomenon of which the observed or measured data are manifestations (also see Bogen and Woodward 1988, and Woodward 2003, 2011)? In other words, how do we know that the manifested phenomenon is a characteristic of the object, rather than a phenomenon that only results from the interaction between object and apparatus? As a consequence, is it really possible to clearly distinguish between the theoretical understanding of an instrument and the observations made of the object by means of it?

Similarly, the assumption that *causal understanding* of the object is derived from observations made by means of instruments (e.g., Hacking 1983, Woodward 2003) relies on the idea that observations of the object are produced by means of an interaction between the object and the instrument. Again, what is the contribution of the interaction between the object and the instrument (e.g., between the electron and the apparatus)? How do we know that instruments present us with causal understanding of the object? For, when using very sophisticated instruments in scientific experiments it is not always obvious where `object', `Nature' or `world' begins and technology ends. Can they be distinguished at all? In many cases, rather than manipulating the object under study in our experiments, the apparatus is manipulated. How do we know that – and *how* exactly – the object is manipulated by means of the instrument?

Rom Harré (1998, 2003) argues that the mentioned distinction is only legitimate for situations in which an ontological distinction can be made between the object under study and the instrument used to examine it. In his view, this is possible for observation of properties of objects by means of microscopes and thermometers, since the instrument and the object under study can be clearly distinguished. But it is more difficult with observations made by means of a cyclotron. Below (in Section 7.i), his view will be outlined in a bit more detail.

The issue of whether a clear distinction between instrument and object is always possible also leads to the question of whether theoretical knowledge can be generated about the object independent of the instruments by means of which the object has been studied. The problems raised suggest that the meaning of a theoretical concept may be local and entangled with a description of the technological instrument. Differently put, we may ask whether theoretical concepts produced in a specific experimental setting have a ‘non-local’ meaning. Radder (1996, 2003) argues against this suggestion. He defends the view that theoretical concepts can be abstracted from the original experimental practice since their meaning becomes non-local as soon as an experimental result is replicated in completely different circumstances – therefore, according to Radder, the theoretical meaning cannot be reduced to the technological level. Below, I will sketch arguments in favour of the opposite view, which assumes that theoretical concepts acquire part of their meaning from the operational definitions of the instruments (also see Chang 2009a). What is more, the empirical and theoretical understanding of the instruments as part of the meaning of theoretical concepts actually explains the possibility of 'replicating experimental results under completely different circumstances.'

7. A Phenomenon-Oriented Perspective: The Material Role of Instruments in Science

i. Epistemic Functions of Instruments

In a theory-oriented positivistic view, only two elements of science are considered: observations and theories. Instruments and experiments are used to test theories, theories are about 'nature' or 'world', and instruments can be clearly distinguished from the object ('Nature' or 'world') under study. So far, the theory-ladeness of observations by means of instruments has been discussed. In Section 6.iv, a related but different question emerged, namely: To *what* does the empirical and theoretical knowledge produced in modern physical experiments relate? Does it relate to the object under study, or the phenomena produced through the interaction between the object under study and the instrument? Hence, the alleged distinction between the instrument and the object, property or process under study is problematic for several reasons: (1) usually, instruments cannot be considered as a mere window on the world; (2) often there is an interaction between the object, property or process under study and the instruments by means of which it is investigated; and (3) in some cases, this interaction, or even the mere technological instrument, produces a phenomenon that does not exist in nature, but becomes itself the object of investigation.

Apparently, instruments have different kinds of epistemic roles in experimental practices. This makes relevant a classification of technological instruments according to their epistemic function. Heidelberger (2003) distinguishes two basic forms of experiments. Firstly, in a theoretical context, instruments have a representative role; their epistemic goal is to *represent* symbolically the relations between natural phenomena and thus to better understand how phenomena are ordered and related to each other. Examples of these instruments are clocks, balances, and measuring rods. Secondly, in causal manipulation by means of instruments, these instruments are used in discoveries and can be distinguished between (a) instruments that have a constructive function (when phenomena are manipulated) and imitative instruments (producing effects in the same way as they appear in nature, without human intervention), and (b) instruments that are used to fulfil a productive function of phenomena that are usually not in the human experience; these are either known phenomena although in circumstances where they have not appeared before – e.g. microscopes –, or unknown phenomena – e.g. Roentgen's production of unknown effects.

In order to address cases in which objects and instruments are entangled, Harré (2003) proposes a classification of instruments based on distinct ontological relationships between laboratory equipment and 'the world'. In his view epistemic functions are derived from ontological relationships. Firstly he distinguishes between *instrument* and *apparatus*. An 'instrument' is defined as detached from the world to be studied, whereas an 'apparatus' is defined as being part of it. (1) 'Instruments' measure either primary qualities (e.g. representing a shape with a microscope) or secondary qualities (e.g. measuring temperature with a thermometer or detecting the presence of acidity with litmus paper). (2) 'Apparatus', on the other hand, are material models of the systems of the world. Regarding 'apparatus', Harré distinguishes between (a) those that are domesticated versions of natural systems (e.g. Drosophila colonies in the laboratory), and (b) Bohrian artefacts that produce phenomena which should not be regarded as the manifestation of a potentiality in the world but as properties of a novel kind of entity, the 'apparatus/world complex'.

Based on the similarities of classifications by authors such as Heidelberger and Harré, I propose a distinction between three types of technological instruments in scientific practices, which I have called *Measure*, *Model* and *Manufacture* (Boon 2004). 'Measure' is a category of instruments that measure, represent or detect certain features or parameters of an object, process or natural state. 'Model' is a type of laboratory system designed to function as a material model of either natural or technological objects, processes or systems. 'Manufacture' is a type of apparatus that produces a phenomenon that is either conjectured from a new theory or a newly produced phenomenon not as yet theoretically understood. The distinction between these types is based on differences in their epistemic and material function in experimental research. ‘Measure’s function is to generate data, for instance values of physical variables under specified conditions. ‘Model’s function is to generate scientific knowledge about a model system, either natural or technological. Somewhat provocatively, I suggested in Boon (2004) that instruments of the manufacture type aim at ontological claims, that is, experiments with manufacture type of devices aim to demonstrate the existence of building blocks or fundamental processes in physical reality. An example of the latter is super-conduction.

Currently, I would add that this interpretation of the epistemic role of instruments of the manufacture type is too narrow. The given interpretation supports a clear distinction between the object and the instrument, and as such it is appropriate to assume that the instrument enables the discovery of the object. But at present, I deny that it makes sense to think of a phenomenon such as super-conduction as existing independent of crucial aspects of the technological instruments producing it. Many of the physical phenomena studied in our laboratories require very specific physical conditions to manifest – these conditions may either occur in nature, or be reproduced by means of technological instruments, or even, never occur in nature but only by means of technological instruments. In any case, as I will argue below, such phenomena are always understood in terms of the physical conditions that bring them about.

My current view on the epistemic role of instruments is close to Cartwright’s notion of nomological machines and Harré’s ideas of Bohrian artefacts. Yet, recognizing that many of the phenomena discovered and investigated in our laboratory are of technological interest asks for a broader perspective on their role in scientific practices. They are no longer just a means for proving theories. Instead, in technoscientific research, the development of theories is often entangled with the development of instruments that produce technologically relevant phenomena.

ii. Epistemic Things and Tools

Although Hacking emphasizes both intervention with and the materiality of instruments and studied objects, and Cartwright (1983, 1989, 1999) stresses that scientific laws are interconnected with the instruments that produce them, their views are still primarily embedded in the ‘theory-oriented’ perspective on science. Rheinberger (1997) broadens the perspective. Similar to Hacking and Cartwright, he emphasizes materiality and manipulability as well as the interconnectedness of instruments and knowledge – but he also enlarges the epistemic role of technological instruments:

> "Experimental systems are to be seen as the smallest integral working units of research. As such they are systems of manipulation designed to give unknown answers to questions that the experimenters themselves are not yet able clearly to ask. ... They are not simply experimental devices that generate answers; experimental systems are vehicles for materializing questions. *They inextricably cogenerate the phenomena or material entities and the concepts they come to embody*. Practices and concepts thus 'come packaged together.'… It is only the process of making one's way through a complex experimental landscape that scientifically meaningful simple things get delineated; in a non-Cartesian epistemology, they are not given from the beginning" (Rheinberger 1997, 28, my emphasis).

For describing this epistemic function of experiments and technological instruments, Rheinberger introduces the notion of 'epistemic things' (also see Baird and Thomas 1990).

Here it is important to distinguish Rheinberger's (1997) notion of 'epistemic things' from my own notion of 'epistemic tools' (Boon 2012, and see below). Whereas an epistemic tool is a tool for thinking (e.g. for thinking about possible interventions with phenomena and/or instruments, and for predicting the outcomes of those interventions), an epistemic thing in Rheinberger's writing is a technological thing, an experimental device, a research object or a scientific object. Epistemic things are material entities or processes – physical structures, chemical reactions, biological functions – that constitute the objects of inquiry. Epistemic tools, on the other hand, are descriptions or pictures (e.g., empirical knowledge, laws, theoretical concepts, scientific models and theories) that are constructed such that we can use them in performing epistemic tasks.

Although the use of these two terms may be somewhat confusing, they add to each other in an account of scientific practices that explains, firstly, in what sense the development of technological instruments and knowledge go hand-in-hand, and secondly, how it is possible that the results of scientific research can be utilized and further developed into high-tech applications.

iii. Theoretical Concepts and Technological Instruments.

In the introduction to this chapter, I suggested that alongside their epistemological function in developing and testing scientific theories and models, technological instruments play a material role in producing specific physical phenomena that may be of interest for developing new technological functions. In a phenomenon-oriented perspective on science, scientific research aims at measuring and/or producing physical phenomena by means of technological instruments, and at understanding both the phenomena and the workings of the instruments to such extent that they (i.e., the instrument and the phenomenon) can be built, controlled, created, calibrated and/or otherwise manipulated.

In a theory-oriented perspective on science, the theory-ladeness of experimental observations in testing theories is problematic. Sections 4-6 presented an outline of how authors in the *New Experimentalist* movement include the role of instruments and experiments when addressing this problem. Yet, accounting for the role of instruments makes the problem worse, as it has become very obvious that instruments are not windows onto the world but are productive themselves. Chang (2004) even argues that the role of instruments in measurement is a locus where “the problems of foundationalism are revealed with stark clarity.” The chance to solve the theory-ladeness problem is thus greatly reduced. In a ‘phenomenon-oriented’ perspective, attention is paid to the role of scientific instruments in the material production of physical phenomena. The theory-ladeness of observing these phenomena in experiments may thus be less problematic. Nonetheless, even in this alternative perspective the question remains of how we should account for *observing new phenomena*, as ‘observing’ them involves the formation of a theoretical concept, which requires theory. In other words, how are new, (technologically relevant) *theoretical concepts* such pseudo-elasticity and super-conductivity formed?

Hacking (1992) argues that observations, instruments and theories are ‘tailored together’ in order to produce a stable fit, but does not explain how the tailoring together occurs. Chang (2004) convincingly shows by means of detailed historical studies that the development of an instrument (the thermometer) is entangled with the production of empirical and theoretical knowledge (in thermodynamics). As an alternative to what he calls ‘foundationalism’, Chang proposes “a brand of coherentism buttressed by the method of ‘epistemic iteration’. In epistemic iteration we start by adopting an existing system of knowledge, with some respect for it but without any firm assurance that it is correct; on the basis of that initially affirmed system we launch inquiries that result in the refinement and even correction of the original system. It is a self-correcting progress that justifies (retrospectively) successful courses of development in science, not any assurance by reference to some indubitable foundation.” (Chang, 2004, 6)

In a similar way, several authors have drawn close connections between experimentation and the formation of theoretical concepts. In this manner, they aim to explain: (1) how theoretical concepts are formed in experimental practices, (2) how the formation of scientific concepts goes hand-in-hand with the development of technological instruments (e.g., Feest, 2008, 2010, 2011), (3) how theoretical concepts themselves play a role in investigating the phenomena to which they supposedly refer (e.g, Feest 2008, 2010, and Boon 2012), and conversely (4) how material objects are the driving forces in the process of knowledge acquisition (e.g., Rheinberger 1997, Chang 2009b), and also, (5) how in these processes phenomena and theoretical concepts get stabilized (Chang 2009b, Feest 2011).

Feest (2010) makes an important contribution by considering a theoretical concept not firstly as a *definition* of the purported object of research, but as a *tool* in the process of investigating it. In her opinion, theoretical concepts are operational definitions (also see Chang 2009a), which function as tools to this end by providing the paradigmatic conditions of application for the concepts in question. These are cast in terms of a description of a typical experimental set-up thought to produce data that are indicative of the phenomenon picked out by the concept. Accordingly, theoretical concepts are formulated in terms of supposed crucial aspects of the experimental set-up, which includes the technological instruments, and in that manner, according to Feest, they are tools which allow for experimental interventions into the domain of study, thereby generating knowledge about the phenomenon. Like other tools they can be adapted or discarded in the process.

Closely related to this line of thought, Chang (2011) asks why some epistemic objects (cf. Rheinberger, 1997) persist despite undergoing serious changes, while others become extinct in similar situations? Based on historical studies, he defends the idea that epistemic objects such as ‘oxygen’ have been retained due to a sufficient continuity of meaning to warrant the preservation of the same term (in spite of major changes of its meaning), but only at the operational level and not at the theoretical level. Furthermore, Chang argues that it might have done some good to keep phlogiston beyond the time of its actual death. Although Chang does not use this vocabulary explicitly, the reason is that ‘phlogiston’ could have functioned as an epistemic tool enabling different kinds of research questions to those prompted by ‘oxygen’.

Amongst other things, phlogiston could have served "as an expression of chemical potential energy, which the weight-obsessed oxygen theory completely lost sight of."[5]

In a similar line, Joe Rouse (2011), asks the old question of how theoretical concepts acquire content from their relation to experience – how does 'conceptual articulation' occur? Rouse's critical remark about a positivistic philosophy of science is that "before we can ask about the empirical justification of a claim, we must understand *what* it claims." According to Rouse, positivistic philosophy of science treats conceptual articulation as an entirely linguistic or mathematical activity of developing and regulating inferential relations among sentences or equations. In opposition, Rouse argues that conceptual articulation and empirical justification by means of experimentation and observation cannot be divided in this manner. He first argues that the problem of observation should be transformed by understanding the sciences' accountability to the world in terms of experimental and fieldwork practices. Secondly, he points out that this transformation shows that conceptual articulation is not merely a matter of spontaneous thought in language or mathematics (and thus not merely intra-linguistic); instead, experimental practice itself can contribute to the articulation of conceptual understanding (see for similar ideas, Van Fraassen 2008, 2012, and Massimi 2011).

Following up on these ideas, I have proposed that the formation of theoretical concepts involves interplay between experimental observations and 'partial' conceptual, empirical and theoretical knowledge of the working of an instrument or experimental set-up. At the outset, the latter kinds of knowledge enable scientists to recognize the experimental observations as of a certain type of phenomenon, such as elastic behaviour or electrical conduction of a material. The relevant point is that the initial interpretation of the data is enabled and guided by conceptual, empirical and theoretical knowledge of the instrument and/or experimental set-up. At the same time, this knowledge enables the scientist to recognize that the experimental

---

[5] Also see Pickering (1984), who makes a claim similar to Chang (2009). Based on his historical analysis of how the concept of quark has been constructed, he argues that the emergence of the quark idea was not inevitable. He believes that in the early 1970s some options were open to high-energy physics such that physics could have developed in a non-quarky way. Important to this argument is his denial of the view of experiments as the supreme arbiter capable of proving scientific claims, for instance, to the existence of entities such as quarks. Instead, according to Pickering, the quark idea established within a preferred theoretical framework (the gauge theory) that affects how a possible interpretation of experimental data is judged.

Also see Boon (forthcoming), in which I analyze the controversy between Pickering (1984) and Hacking (2000) on the question of to which extent the entities in successful theories are inevitable or contingent. As an alternative to Hacking's realism, I propose epistemological constructivism, which is in alignment with those of Chang (2009b) and Rouse (2011).

observations are at variance with empirically known behaviour, thus pointing at a new kind of physical phenomenon. Finally, formation of a theoretical concept of a phenomenon involves interpreting the experimental observations by employing relevant conceptual, empirical and theoretical background knowledge. In other words, the leap from experimental observations to new theoretical concepts for describing new kinds of physical phenomena builds on empirical knowledge and theoretical understanding of the instruments and experimental set-up. As a consequence, theoretical concepts remain connected with knowledge of supposedly relevant physical conditions and aspects of the instrument and/or experimental set-up by means of which it has been produced.

iii. Conclusions

In this chapter, my goal is not an exhaustive overview of literature in the philosophy of science that addresses the role of technological instruments in science. Rather, I have aimed to present an overview of ideas that explain the entangled epistemic and material role of instruments and experiments in scientific research practices. For a long time, the philosophy of science has ignored the role of technological instruments. What is more, both scientists and philosophers have left us with a sense of awe but also confusion about the technological achievements of science. How is it possible that, by means of mere theoretical knowledge we can design and build previously inconceivable technological devices? These apparent miraculous achievements have been an important argument for the so-called miracle argument in the philosophy of science: such incredible successes can only be explained when assuming that our most successful scientific theories are true and the entities proposed in these theories really exist. Yet, based on a better understanding of the role of technological instruments in the formation of scientific knowledge (such as, theoretical concepts, empirical knowledge and scientific models of phenomena), alternative explanations come into view. Possibly, an explanation of the remarkable technological achievements could be less reliant on the character of theories, and more dependent on the crucial material and epistemic role of technological instruments in scientific research practices.

Acknowledgments

The writing of this article was financially supported by a Vidi grant from the Dutch National Science Foundation NWO). I am grateful to the ZIF Bielefeld and the interdisciplinary research group "Science in the Context of Application" who supported part of this research. I would also like to thank my language editor, Claire Neesham at Centipede Productions.

References

Ackermann, R.J. (1985). *Data, Instruments and Theory: A Dialectical Approach to Understanding Science*. Princeton, Princeton University Press

Ackermann, R. (1989). The New Experimentalism. *The British Journal for the Philosophy of Science* **40**(2): 185-190.

Baird, D. and F. Thomas (1990). Scientific Instruments, Scientific Progress and the Cyclotron. *British Journal for the Philosophy of Science* **41**(2): 147-175.

Baird, D. (2003). Thing Knowledge: Outline of a Materialist Theory of Knowledge. In: *The Philosophy of Scientific Experimentation*. H. Radder (ed.). Pittsburgh, University of Pittsburgh Press**:** 39-67.

Baird, D. (2004). *Thing Knowledge: A Philosophy of Scientific Instruments*. University of California Press.

Bogen, J. and J. Woodward (1988). Saving the Phenomena. *The Philosophical Review* 97 (2): 303 – 352.

Boon, M. (2004). Technological Instruments in Scientific Experimentation. *International Studies in the Philosophy of Science* **18**(2&3): 221-230.

Boon, M. (2011). In Defence of Engineering Sciences: On the Epistemological Relations between Science and Technology. *Techné: Research in Philosophy and Technology*. **15**(1): 49-71.

Boon, M. (2012). Scientific Concepts in the Engineering Sciences: Epistemic Tools for Creating and Intervening with Phenomena. In: *Scientific Concepts and Investigative Practice* U. Feest and F. Steinle (eds.). Berlin, New York: Walter De Gruyter GMBH & CO. KG, Series: Berlin Studies in Knowledge Research. 219-243.

Boon, M. (forthcoming). Contingency and Inevitability in Science – Instruments, Interfaces and the Independent World. In: *Contingency – Science as it could have been*. L. Soler *et.al.* (eds.)

Carrier, M. (1998). New Experimentalism and the Changing Significance of Experiments: On the Shortcomings of an Equipment-Centered Guide to History. In: *Experimental Essays - Versuche zum Experiment*. M. Heidelberger and F. Steinle. Baden-Baden, Nomos: 175-191.

Carrier, M. (2001). Error and the Growth of Experimental Knowledge. *International Studies in the Philosophy of Science*: **15**(1): 93-98.

Cartwright, N. (1983). *How the Laws of Physics Lie*. Oxford, Clarendon Press, Oxford University Press.

Cartwright, N. (1989). *Natures Capacities and their Measurement*. Oxford, Clarendon Press, Oxford University Press.

Cartwright, N. (1999). *The Dappled World. A Study of the Boundaries of Science*, Cambridge University Press.

Chalmers, A. (2003). The Theory-Dependence of the Use of Instruments in Science. *Philosophy of Science* **70**(3): 493-509.

Chang, H. (2004). *Inventing Temperature: Measurement and Scientific Progress*. Oxford, Oxford University Press.

Chang, H. (2009a), Operationalism, *The Stanford Encyclopedia of Philosophy*. E.N. Zalta (ed.), URL = <http://plato.stanford.edu/archives/fall2009/entries/operationalism/>.

Chang, H. (2009b). The Persistence of Epistemic Objects through Scientific Change. *Erkenntnis*. **75**: 413–429.

Feest U. (2008). Concepts as Tools in the Experimental Generation of Knowledge in Psychology. In: *Generating Experimental Knowledge*. U. Feest, G. Hon, H.J. Rheinberger, J. Schickore & F. Steinle (eds.). MPI-Preprint 340: 19-26.

Feest U. (2010). Concepts as Tools in the Experimental Generation of Knowledge in Cognitive Neuropsychology. *Spontaneous Generations: A Journal for the History and Philosophy of Science*. **4**(1): 173-190.

Feest, U. (2011). What exactly is Stabilized when Phenomena are Stabilized? *Synthese*: *An International Journal for Epistemology, Methodology and Philosophy of Science.* **182**(1): 57-71.

Frigerio, A., A. Giordani and L. Mari (2010). Outline of a General Model of Measurement. *Synthese*: *An International Journal for Epistemology, Methodology and Philosophy of Science.* **175**:123–149.

Franklin, A. (1986). *The Neglect of Experiment*. Cambridge, New York, Cambridge University Press.

Franklin, A. (2002). Experiment in Physics. *The Stanford Encyclopedia of Philosophy*. E.N. Zalta (ed.), URL = <http://plato.stanford.edu/archives/win2012/entries/physics-experiment/>.

Franklin, L. (2005). Exploratory Experiments. *Philosophy of Science*. **72**(5): 888-899.

Galison, P. (1987). *How Experiments End*. Chicago, London, University of Chicago Press.

Galison, P. (1997). *Image and Logic: A Material Culture of Microphysics*. Chicago, Chicago University Press.

Giere, R.N. (1988). *Explaining Science*. Chicago and London: The University of Chicago Press.

Hacking, I. (1983). *Representing and Intervening : Introductory Topics in the Philosophy of Natural Science.* Cambridge, Cambridge University Press.

Hacking, I. (1992). The Self-vindication of the Laboratory Sciences. In: *Science as Practice and Culture*. A. Pickering (ed.). Chicago: University of Chicago Press, 29-64.

Hacking, I. (2000). How Inevitable are the Results of Successful Science? *Philosophy of Science*. **67**, S58–S71.

Harré, R. (1998). Recovering the Experiment. *Philosophy* **73**(285): 353-377.

Harré, R. (2003). The Materiality of Instruments in a Metaphysics for Experiments. In: *The Philosophy of Scientific Experimentation*. H. Radder (ed.). Pittsburgh, University of Pittsburgh Press**:** 19-38.

Heidelberger, M. (2003). Theory-Ladenness and Scientific Instruments. In: *The Philosophy of Scientific Experimentation*. H. Radder (ed.). Pittsburgh, University of Pittsburgh Press**:** 138-151.

Hon, G. (1998). Exploiting Errors: Review of Deborah Mayo's Error and the growth of experimental knowledge. *Studies in the History and Philosophy of Science* 29(3): 465-479.

Hon, G. (2003). The Idols of Experiment: Transcending the 'Etc. List'. In: *The Philosophy of Scientific Experimentation*. H. Radder (ed.). Pittsburgh, University of Pittsburgh Press**:** 174-197.

Ihde D. (1991). *Instrumental Realism: The Interface between Philosophy of Science and Philosophy of Technology.* Bloomington and Indianapolis: Indiana University Press.

Ihde D. and E. Selinger (eds.) (2003). *Chasing Technoscience. Matrix for Materiality*. Bloomington and Indianapolis: Indiana University Press.

Ihde, D. (2009). From da Vinci to CAD and Beyond. *Synthese: An International Journal for Epistemology, Methodology and Philosophy of Science*, 168(3), 453-467.

Krantz, D.H., Luce, R.D., Suppes, P., & Tversky, A. (1971). *Foundations of Measurement (Vol. I)*. New York: Academic Press.

Kuhn, T.S. (1970). *The Structure of Scientific Revolutions, second edition*. Chicago: The University of Chicago Press.

Lacey, H. (2012). Reflections on Science and Technoscience. *Scientiae Studia: Revista Latino-Americana De Filosofia E História Da Ciência*, 10: 103-28.

Lange, R. (2003). Technology as Basis and Object of Experimental Practices. In: *The Philosophy of Scientific Experimentation*. H. Radder (ed.). Pittsburgh, University of Pittsburgh Press**:** 119-137.

Luce, R.D. Krantz. D.H., Suppes, P. & Tversky, A. (1990). *Foundations of measurement (Vol. III)*. San Diego: Academic Press.

Massimi, M. (2011). From Data to Phenomena: A Kantian stance. *Synthese*: *An International Journal for Epistemology, Methodology and Philosophy of Science.* 182(1): 101-116.

Mayo, D.G. (1994). The New Experimentalism, Topical Hypotheses, and Learning from Error. *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association* 1994: 270-279.

Mayo, D.G. (1996). *Error and the Growth of Experimental Knowledge*. Chicago, University of Chicago Press.

Mayo, D.G. (2000). Experimental Practice and an Error Statistical Account of Evidence. *Philosophy of Science* **67**(3): S193-S207.

Nordmann, A. (2012). Object Lessons: Towards an Epistemology of Technoscience. *Scientiae Studia: Revista Latino-Americana De Filosofia E História Da Ciência*, **10**: 11-31.

Pickering, A. (1984). *Constructing Quarks, a Sociological History of Particle Physics*. Chicago & London: University of Chicago Press.

Popper, K.R. (1959). *The Logic of Scientific Discovery*. London, Hutchinson.

Radder, H. (1996). *In and About the World: Philosophical Studies of Science and Technology*. Albany NY: State University of New York Press.

Radder, H. (ed.) (2003a). *The Philosophy of Scientific Experimentation*. Pittsburgh, University of Pittsburgh Press.

Radder, H. (2003). Toward a More Developed Philosophy of Scientific Experimentation. In: *The Philosophy of Scientific Experimentation*. H. Radder (ed.). Pittsburgh, University of Pittsburgh Press**:** 1-18.

Radder, H. (2004). Book review: Chasing Technoscience. Matrix for Materiality. *Philosophy of Science*, **71**(4), 614-619.

Rheinberger, H.J. (1997). *Toward a History of Epistemic Things: Synthesizing Proteins in the Test Tube*. Stanford: Stanford University Press.

Rothbart, D. (2003). Designing Instruments and the Design of Nature. In: *The Philosophy of Scientific Experimentation*. H. Radder (ed.): 236-254.

Rouse, J. (1987). *Knowledge and Power: Towards a Political Philosophy of Science*. Ithaca: Cornell University Press.

Rouse, J. (2011). Articulating the World: Experimental Systems and Conceptual Understanding. *International Studies in the Philosophy of Science*. **25**(3): 243-254.

Steinle, F. (2002). Challenging Established Concepts: Ampere and Exploratory Experimentation. *Theoria* **17**(44): 291-316.

Steinle, F. (2006). Concept formation and the limits of justification: the two Electricities. *Archimedes.* **14**(III): 183-195.

Suppes, P., Krantz. D.H., Luce, R. D., & Tversky, A. (1990). *Foundations of measurement (Vol. II)*. New York: Academic Press.

Van Fraassen B. (2008). *Scientific Representation*. Oxford: Oxford University Press.

Van Fraassen B. (2012). Modeling and Measurement: The Criterion of Empirical Grounding. *Philosophy of Science* **79**(5): 773-784.

Woodward J.F. (2003). Experimentation, Causal Inference, and Instrumental Realism In: *The Philosophy of Scientific Experimentation*. H. Radder (ed.). Pittsburgh, University of Pittsburgh Press: 87-118.

Woodward J.F. (2011). Data and Phenomena: a Restatement and Defense. *Synthese* **182**(1): 165-179.

Pitt, J.C. (2000). *Thinking about technology: Thinking about the foundations of a philosophy of technology*. New York: Seven Bridges Press.