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Generative Role of Experiments in Physics and in Teaching Physics: A Suggestion for Epistemological Reconstruction

ISMO T. KOPONEN and TERHI MÄNTYLÄ
Department of Physical Sciences, University of Helsinki, Finland

Abstract. In physics teaching experimentality is an integral component in giving the starting point of knowledge formation and conceptualization. However, epistemology of experiments is not often addressed directly in the educational and pedagogical literature. This warrants an attempt to produce an acceptable reconstruction of the epistemological role of experiments in physics by drawing insight from history and philosophy of physics. Towards that end, the experiments' role in the 19th-century physics is discussed. We propose here a reconstruction, which is based on the idea that in epistemology of experiments the inductive-like *generative justification of knowledge* is central. A generative view makes it possible to retain those aspects of experiments which make them purposeful for learning and can give a starting point for students' own construction of knowledge. The reconstruction also helps to conceive the experiments with their correct historical role and helps to bring back the generative use of experiments in teaching, which, after all, has never vanished from the practice of physics.

1. Introduction

Experiments have so central a role in physics education that hardly any textbook fails to mention that physics is an 'experimental science' and that in physics 'knowledge is based on experiments'. Of these statements there seems to be a general agreement among physicists doing their science, philosophers interpreting the physicists' activities, and finally, science educators trying to give a picture of physics to their students. However, as soon as the epistemological role of experiments needs to be made more definite, there is a broad spectrum of views ranging from experiments as a basis for simple inductions to views that experiments are used for refuting theories. Therefore, there is a need to pay more attention to the epistemology of experiments in physics education.

The verificatory role of experiments is the preferred physicists' stance, expressed by Feynman et al. (1963) mentioning: 'The test of all knowledge is experiment. Experiment is the sole judge of scientific truth'. Physicists often mention experiments in the role of 'supporting' theory (Einstein 1970;

Weinberg 1993), but the idea that experiments are for refuting theories by falsification (Popper 1935/2002) is, however, denied (Einstein 1970, pp. 21–23; Weinberg 1993, p. 102). The 'textbooks' science', on the other hand, follows the scheme of verificatory justification, and it displays physics as a logical chain of steady progress, experiments verifying the predictions based on theory (Kuhn 1996). Contrary to this conception, inductivist views about the role of experiments are common in the 19th-century physics literature (see e.g. Robin 1904; Duhem 1914/1954). However, towards the end of the 19th century, there was a shift to hypothetical-deductive views of science, and questions related to the logic of discovery were set aside in favour of the logic of justifying theoretical knowledge (Suppe 1977; Giere 1988).

During two decades there has been increasing criticism towards the predominant view that the main role of experiments is in verifying, or refuting knowledge; the epistemology of experiments and philosophy of experiments is far richer than depicted in standard accounts of science (Hacking 1983; Franklin 1986, 1999; Giere 1988, 1999; Gooding et al. 1993). Recently it has been suggested that the inductivist ideal, or what can be called – from a wider perspective – the '*generative knowledge justification*' may still be an important part of doing science (if not in speaking about science), and has actually never been abandoned (Nickles 1993). These notions suggest that, also in physics education, there is a need to reconsider and reanalyse the role of experiments in generating new knowledge and in forming the meaning of theoretical concepts.

Another reason to pay attention to the epistemology of experiments is due to fact that today questions related to the role of experiments in generating knowledge is not often addressed directly in the physics education literature. Educational literature concentrates, of course, predominantly on educational aspects of doing experiments; on their role on learning and on the practical questions related to teaching. These questions are often discussed in the framework referred to as the personal constructivist view on learning (Trumper 2003). Within personal constructivism many problems related to learning have been resolved, and there are also informative studies on physics education of laboratory work used to support students' cognitive process of forming knowledge (Van Heuvelen 1991; Redish 1994, 1999; Hammer 1996; Sokoloff & Thornton 1997; McDermott et al. 2000). However, questions addressed within personal constructivism are often separate from the epistemological problem concerning the origin of objective (or intersubjective and shared) knowledge that science produces and how this knowledge is justified. There is still a need for an epistemological reconstruction of the role of experiments in physics, truthful to their role as conceived in the history of physics.

We propose here one possibility for a reconstruction, which can be used as a basis for the planning of educational experiments. It is based on the idea, that we must pay more attention to the *generative justification of knowledge*. That is to say, we must pay more attention to the phenomenological physics and empiricism as exemplified in the practice of the 19th-century physics. We discuss the history and philosophy of physics at length, which is needed to make these arguments plausible and acceptable. We believe that the resulting reconstruction helps to avoid the pitfalls of simple inductivism and the narrow scope of verificatory use of experiments. It also retains those aspects of experimentation, which make them purposeful for learning by giving a starting point for students' own construction of knowledge.

2. Experiments and Experimentation in Physics Education

Demonstrations and practical work in the laboratory have long been accepted as an integral part of learning physics (Wellington 1998; Trumper 2003) and it is hard – even impossible – to imagine as reasonable the possibility of physics teaching without experimental work. Many reforms of physics education have relied on the conviction that learning can be improved through developing ways in which experiments are conducted in the physics classroom as well as by developing suitable study material and experimental models of teaching (Duit & Confrey 1996). The reformers and designers of new curricula have quite often drawn support for their ideas from constructivist views of learning (for reviews, see Niaz et al. 2003; Trumper 2003). Researchers do not agree, however, on the significance of experimental work in science education (Lazarowitz & Tamir 1994; White 1996). It has been found that practical work have little impact on student understanding (Watson et al. 1995), that the usefulness of laboratory work towards the goal of learning scientific concepts is hard to interpret and somewhat uncertain (Hodson 1993, 1996), and that the benefits of laboratory work on students' understanding about the character of physics knowledge are also questionable (Millar 1989). The poor outcomes are suspected to result from the way experiments are conducted. In some cases the apparent reason for ineffectiveness is the too straightforward verificatory use of experiments; the cognitive demand of the laboratory in particular tends to be low, because experiments are used mainly as a way to confirm simply what has already been taught (Lazarowitz & Tamir 1994; Berry & Sahlberg 1996; Trumper 2003). The other extreme, the oversimplified inductive use of experiments, as in the so-called 'discovery learning' originating in the 1960s, has also proved to be an unsuccessful approach. Its failure has been ascribed, to a large degree, to the false idea of inductivism in science and the far-stretched idea of students as 'novice researchers' (Hodson 1992; Niaz et al. 2003; Trumper 2003).

2.1. EDUCATIONAL GOALS WITHIN PERSONAL CONSTRUCTIVISM

Many researchers and educators (Redish 1994, 1999; Hammer 1996; Hestenes 1998) have recognized the need for a theoretical framework for physics education. Towards this end, Redish (1994) suggests the use of principles based on cognitive studies, which concern students' understanding and learning processes. The framework acknowledging the importance of personal cognition on learning has developed gradually during the last two decades, and according to Trumper (2003), it can be viewed as a version of 'the personal constructivist model of learning' or simply 'personal constructivism'. A key feature of it is that 'it begins with what students know, continue with what they can learn by arranging their interaction with the physical world around them, and connect this learning to the underlying principles of scientific knowledge' (Trumper 2003, p. 650). Personal constructivism can be taken, rather, as a guide regarding how to teach, instead of what to teach, and it is useful to separate constructivist ideas about learning from constructivist epistemology (Gil-Perez et al. 2002; Trumper 2003). Adoption of personal constructivism therefore does not mean acknowledging the constructivist epistemology, which should be rejected here as a flawed conception of knowledge (see e.g., Matthews 1997, 2000; Nola 1997; Niaz et al. 2003).

Based on personal constructivism, laboratory activities which are conceptually more demanding than simple verifying experiments has been proposed by many authors (Arons 1993; Redish 1994; Sokoloff & Thornton 1997). Different authors stress the educational goals of laboratory work differently, but the commonly accepted goals are that students should have (1) an opportunity to participate in the acquisition and construction of knowledge, (2) to see how that knowledge is reached and justified, and (3) to understand how the meaning of concepts and laws in physics is generated. In reaching these goals, students' social interaction has a crucial role. Students should have an opportunity to express their ideas in their own words, to reflect about one's own learning and correct errors, and make explicit their own intuitive reasoning (Redish 1994, 1999; Hammer 1996; McDermott et al. 2000).

Effective teaching models, in order to reach educational goals, should also pay attention to cognitive aspects of learning, such as organizing knowledge (Reif 1987, 1995; Van Heuvelen 1991; Bagno et al. 2000) and processes of producing knowledge (Etkina et al. 2002; May & Etkina 2002). Within these teaching models, the students' learning process is often supported by using organizing principles and their visual representation, e.g. concept maps and drawings (Reif 1987, 1995; Van Heuvelen 1991; Bagno et al. 2000).

Teaching models stressing the processual aspects of producing knowledge are often based on the investigative nature of conceptualization and on observations as a source of knowledge. For example Etkina et al. (2002) and May and Etkina (2002) combine different types of experiments, which are used to guide students to differentiate between observational evidence and inferences, to test inferences experimentally and to see the applicability of their ideas. McDermott et al. (2000) have expressed similar views, and they also note the need to construct concepts starting from observations. Concept formation proceeding from observations and experiments is, however, not the only way to promote active student participation and the investigative character of learning. A good example is provided by modeling methodology, where the major role of experiments is to test and validate models, and there is thus a clear predominance towards the hypothetical-deductive view on the role of experiments (Hestenes 1992; Wells et al. 1995). These examples show that the educational goals within personal constructivism can be combined with differently biased epistemological goals, based on different views concerning the justification of knowledge.

2.2. EPISTEMOLOGICAL GOALS OF LABORATORY WORK

The educational goals as outlined above within personal constructivism do not, however, guarantee the authenticity of physics experiments in teaching. In addition to these, two additional epistemological goals need to be specified, requiring that 4 experiments are conceived as a source of knowledge, but not only this; it needs to be recognised that 5 experiments as a form of reasoning are conceptually comparable to theorizing. Through the historical and philosophical analysis, we argue that the appropriate epistemology fulfilling these requirements can be based on experiments in the form of the generative justification of knowledge. In order to motivate and justify the suggested goals it is necessary to analyze in more detail the role of experiments in physics and draw insight on it from the *history and philosophy of physics*. On this basis, it becomes possible to produce a *reconstruction*, truthful enough to the ways in which experiments are used in physics, but which also pays appropriate attention to *cognitive factors* in learning and the importance of a learner's own active role in learning (Nersessian 1984, 1995; Izquierdo-Aymerich & Adúriz-Bravo 2003). Of particular importance in the reconstruction are the structures and processes of producing knowledge and suitable ways to represent them for the purposes of learning.

3. A Philosophical Primer for the Epistemology of Experiments

The rich variety of experiments' epistemologies is not captured by any coherent philosophical scheme; experimental science is too complex for this. Nevertheless, we need coherent perspectives on the epistemology of experiments and to connect these to relevant philosophical views. We give here an overview of those viewpoints (to be numbered from P1 to P6), which form the basis of the reconstruction to be produced. We stress here the role of experiments in knowledge construction. The viewpoint chosen rejects the strict distinction between the 'context of discovery' and the 'context of justification' (Reichenbach 1951). It has been argued, that this division has led philosophers to overemphasize the role of theory and has led to the 'neglect of experiments' in philosophy (Franklin 1986, 1999; Nickles 1993; Gooding et al. 1993).

P1. *Consequential justification of knowledge is one epistemological role of experiments, but it is not the only one of importance*. The view that the major role of experiments is to verify theoretical predictions (verificatory role of experiments), is called here 'consequential justification of knowledge' following Nickles (1993). The consequential justification of knowledge as the only epistemological role of experiments has been dominant conception of the epistemological role of experiments up to quite recent philosophical writings about physics (see e.g. Hacking 1983; Gooding et al. 1993; Nickles 1993). As a means of justification, it is inherently linked to distinction between 'context of discovery' and 'context of justification' (Reichenbach 1951), which is also the basic assumption behind the so-called Received View (RV) on theories (Suppe 1977). According to RV, the only role of experiments, which yields to meaningful logical analysis, is limited to consequential justification; using experiments to confirm or refute theoretical predictions.

P2. *Finished theories have a stratified hierarchical structure*. The RV conceived science as it was thought to develop: initially consisting of empirical generalizations based on lower-level observations, later theoretical terms are introduced *by definition* and theoretical laws or generalizations are formulated in terms of them. Thus, there is the upward progress and abstraction from particular facts to theory (Suppe 1977, p. 17). The criticism towards the stratified structure of theories as addressed in RV is most often directed towards the possibility to logically deduce the structures of the higher levels from those on the lower level, not to the stratified structure itself. For example, the alternative view for RV suggested by Toulmin (1969) also employs the stratified structure. However, for Toulmin this does not mean that lower-level structures can be *deduced* from the higher-level structures, only that inferences about phenomena can be drawn in accordance with them (Toulmin 1969).

P3. *Observations are theory-laden and recognition of phenomena is guided by theory*. In some alternatives of the RV, the empirical meaning of concepts is of concern. For example, Hanson (1958) has stressed the importance of the process of discovery, where concepts and laws receive their initial meaning. For Hanson, all observations are 'theory-laden' and the recognition of phenomena, observation and facts are guided by theory. According to him, 'physical theories provide patterns within which data appears intelligible'

(Hanson 1958, p. 344). The logic of discovery then consists of fitting the observations and phenomena to existing theoretical patterns (Hanson 1958, p. 90).

P4. *Theories need no interpretations; instead, meaning of concepts and laws is built in through their construction.* The irreparable deficiency of the RV is that it sees theories as uninterpreted formal systems in need of empirical rules of interpretation. Contrary to this, in the so-called Semantic View (SV), the phenomena are addressed in terms of models and attention is guided to the question of how the *match between experiments and theory* is already made by way of construction, through the use of models or in terms of a hierarchy of models (Suppe 1977; van Fraassen 1980; Giere 1988, 1999). As Giere notes, within the SV, it becomes possible to start the construction of meaning from the basic level and proceed to superordinate levels, and 'one does not have to worry about how to put empirical significance into a formal structure if one avoids the initial leap of abstraction away from the meaning that was there all along at the basic level' (Giere 1999, p. 117).

P5. *Experiments and theory are intertwined.* Within the SV, it becomes possible to conceive the construction of theoretical and empirical meanings as being inherently intertwined. The intertwining is particularly clear in empiricist views based on SV, as for example in Constructive empiricism (van Fraassen 1980). Constructive empiricism entails a bi-directional view on experiments, where 'theory is a factor in experimental design' and, on the other hand, 'experimentation is a factor in theory construction' (van Fraassen 1980, p. 77). These views agree with Duhem's version of empiricism, where experiments are also conceived as a 'continuation of theory', and as Duhem notes 'an experiment in physics is not simply the observation of a phenomenon; it is, besides, the theoretical interpretation of this phenomenon' (Duhem 1914/1954, p. 144). Moreover, for Duhem, the use of instruments itself becomes possible only through the theoretical interpretation of phenomena on which their operation is based. These empiricist notions thus characterize well the intertwined role of theory and experiment in physics. *They grant both to theory and to experiment an equal importance in knowledge formation.*

P6. *The generative justification of knowledge is essentially a part of theory construction.* With Hanson's notions about the importance of the process of discovery (P3), augmented with Duhem's and van Fraassen's pictures of how the results of experiments are matched with theory (P5), we are coming close to the 19th-century empiricism and its conceptions of scientific method. The viewpoint emerging from these considerations stresses the context of discovery and the role of experiments therein, but it rejects the simple inductive conception of the production of knowledge. The view of experiments, which stresses the process of discovery and formation of new knowledge, without being trapped within the oversimplified one-directionality of the inductive scheme, is called here *the generative justification of knowledge*, following the suggestion by Nickles (1993). Accordingly, experiments are the basis and source of new knowledge and they are interpreted within the existing theory, but in that process, the body of theoretical knowledge involved also becomes transformed. (Hacking 1983; Nickles 1993). As Nickles outlines, generative justification is constructive; theory is justified by construction, 'directly by reasoning *to* the theory from what we already "know" about the world as well as indirectly by reasoning *from* the theory' (Nickles 1993, p. 306).

4. Historical Support for Generative Justification

In order to find historical support for claims that generative justification of knowledge is an authentic epistemological role for experiments, we provide in the following an overview of the experiments' epistemology in the 19th century. During that era, empiricism was one of the major continental philosophical stances, which not only affected the views of physicists but was also at least partially an outcome of developments in physics methodology. Empiricism thus opens up relevant viewpoints on representing and organizing the empirical knowledge and on the theory construction related to it. If not taken too far, these kinds of empiricist views are not contradictory with moderate realism (Cartwright 1983; Hacking 1983; Fine 1986). Alongside empiricism, however, important advances were made within lines of reductionist and realist views, for example in kinetic theory and atomic theories of matter (Brush 1983). However, because the generative justification is of interest here, we concentrate mainly on empiricism and the lines of thought, which underlie it.

4.1. INVENTION OF THE GENERATIVE USE OF EXPERIMENT

The early generativists, such as Bacon and Newton, maintained that the best starting point for constructing theories is starting from what is already known about the phenomena (Nickles 1993, p. 304). In this sense, Newton's inductive method, which take observations and experiments as a basis for knowledge can be thus taken as a first formulation of generative justification. According to Newton's view, it is possible to deduce law-like representations through inductive generalizations, which embrace the regularities and general recurring features found in nature. In Newton's method, however, the mathematical description of these regularities is separated from the invention of physical explanations. The mathematical descriptions which are inductive generalizations, based on observations, are finally tested against observed facts. Newton's method was long held as an ideal for the physical sciences, if not realizable in its practices, as well as in theory construction (Duhem 1914/1954; Darrigol 2000). The mathematical part of Newton's method was transformed during the 18th century into the powerful 'neo-Newtonian' mathematical physics exemplified by e.g. French 'Laplacian physics' (see also Brush 1983; Smith & Wise 1989; Darrigol 2000). Progress was made through this line of development in theory construction, but the narrowly seen role of experiments eventually hindered new discoveries within it.

In experimental physics, Newton's inductive method was much transformed in the late 18th century and evolved into a more strictly experimental approach, where experimental results were not used as a basis for hypothesis, but instead were taken in a phenomenalist sense; indeed, they were taken as representation of regularities found in different phenomena. This was the dominant form of experimental physics in Germany up to 1830 and its aim was to 'discover new phenomena, examine the nature of phenomena and provide connections between different phenomena', and then on this basis – through induction and generalization – to produce experimental laws (Jungnickel & McCormmach 1986, p. 120).

An interesting case of inductive-like experimentation combined with phenomenological investigations without mathematical representations is provided by Faraday and his research on electromagnetism (Gooding 1990). Faraday's work was prominently free from mathematical theorizing. A marked feature of Faraday's style of experimentation was the exploratory and imaginative use of experimental practices, the possibility to vary and transform the experimental setups and situations. In Faraday's work, the inductive-like, generative experimentality took a form of an inherent logic and coherence of experiments themselves, in a form of 'experimental reasoning' (Gooding 1990; Darrigol 2000). In the history of science, Faraday's experimental method is rather an exception to the rule, but its influence was nevertheless far reaching. It fundamentally affected German experimental research 1830–1860 and encouraged the belief that *phenomenological experimental research can be a source of valuable new knowledge*. In these cases, experiments are conceived in the role of generating new knowledge, which is then epistemologically justified through the method within which it is produced. *This way of conducting experiments with the purpose to produce new knowledge is called generative experimentality in what follows.*

4.2. PERFECTING METHODOLOGY: PRECISION MEASUREMENTS

The full articulation of methodological questions related to acquisition of knowledge through experiments, however, required the development of precision measurements and techniques of instrumentation. The perfection of the methodology of physical measurements took place rapidly 1820–1840 in continental research in France, through the work of such experimentalists as de la Rive and Regnault (Duhem 1914/1954; Darrigol 2000; Chang 2001), and in Germany by Gauss, Ohm and Magnus (Jungnickel & McCormmach

1986). Not only did Gauss affect the German tradition of experimental research concentrating on phenomena, but Regnault's methods also inspired the development of this tradition. A strong impact also came through Faraday's work. Experimental apparatus and measuring devices became a part of the examination of natural phenomena, and it was this type of combination of experiment and theory, which became characteristic to German 'phenomenological' experimental physics (Jungnickel & McCormmach 1986).

The German development parallels the experimental style developed by William Thomson, who also acquired the basic experimental methods from Regnault (Smith & Wise 1989; Chang 2001). For Thomson the goal of the experimental research was the 'systematic observations and experiments, which have for their object the establishment of laws and formation of theories' (Smith & Wise 1989, p. 122). In Thomson's research, neo-Newtonian theory construction had an important role and it unified the experimental and theoretical parts of physics. According to Thomson, the aim of theory was to make possible the inclusion of many experimentally found results in mathematical form, which yielded itself to detailed mathematical analysis. Although Thomson's work was predominantly theoretical, the guidance and support of experimental physics in developing it was substantial (Smith & Wise 1989). The styles of experimentation developed in Germany 1830–1840 and in Britain by William Thomson in the1840s rely both on the generative justification of knowledge (influenced by Newton's and Faraday's work) and, on the other hand, on precise quantitative measurements (influenced by Regnault's work).

4.3. EMPIRICISM AND GENERATIVE JUSTIFICATION

The phenomenological approach on physics found its perhaps most fruitful appearance in research by Helmholtz and Hertz. The ideal of science, according to Helmholtz, was a kind of unification of the scientific method towards objective knowledge, which was made possible through methodological empiricism (von Helmholtz 1886/1995; Jurkowitz 2002). Although Helmholtz's stance was empiricist and his physics phenomenological, it also was firmly rooted in realism and had a strong flavour of reductionism build into it (Heidelberger 1998; Darrigol 2000; Jurkowitz 2002). According to Helmholtz's view – much resembling those of Thomson's – the formation of knowledge started with (1) fact collecting, (2) subsequent organization of facts into more encompassing ones, and (3) construction of restricted laws. It then continued with (4) hierarchical organization of knowledge and (5) inductive inferences towards more general laws and concepts. The existing theory was thus extended so that it became possible to make inferences and predictions in new areas of phenomena, not initially contained the range of validity of the theory (Jurkowitz 2002). Helmholtz's conception of science strongly resembles Whewell's philosophy, which also combines the generative, inductive-like use of experiments with the consequential testing of hypotheses (Whewell 1847).

Helmholtz's empiricist and phenomenological views are reflected in his experimental style, which was at once exploratory and also constrained by theory. In Helmholtz's research new devices are constantly being imagined and designed in response to new problems and with the aim to solve such problems (Darrigol 2000, p. 263). A similar mixture of phenomenology and an exploratory style of experimentation is seen in Hertz's experimental work, very similar to that found in Faraday's work. The important difference, however, is that Hertz made extensive use of theory in analysing the operation of devices and in improving their performance (Buchwald 1994; Darrigol 2000). Helmholtz and Hertz thus managed to retain the fruitful coexistence between methodological empiricism and a certain type of realism, and to connect them with the generative use of experiments. *The advantage of this mixture is that it provides an epistemologically clear relation between theory and experiments.*

Hertz's philosophy of science is in many respects based on elements already present in Helmholtz's philosophical conceptions. In the case of Hertz, however, the empiricist views are combined with the view that theories represent the world in a way which goes beyond the immediate observation and their descriptions (Heidelberger 1998, p. 23). For Hertz, the instrumental use of theory was essential and he thought that a theory 'encompasses the phenomenological or factual content of the theoretical laws without referring to any causes of the phenomena' (Heidelberger 1998, p. 18).

Hertz paid much attention to the empirical adequacy of descriptions, and this care of empirical adequacy is behind the remarkable epistemological clarity and order of his systematic exposition of the theory of electrodynamics (Darrigol 2000). As Heidelberger (1998) has discussed, Hertz thought that physical representations of the theory are necessary, but they can be developed safely only after the descriptive theory was established. The representations thus presuppose a complete mathematical description of experimental results on the phenomenological level. In this respect, Duhem's and van Fraassen's views (see P4 and P5) describe Hertz's approach on theory construction in electrodynamics very well. In addition, the notion of the theory-ladenness of concepts (P3) characterizes well Hertz view on the role of theory in guiding experimentation. Hertz's work thus provides a good example of the generative use of experiments combined with the theoretical analysis of experimental setups and instrumentation.

4.4. GENERATIVE JUSTIFICATION IN THE 20TH-CENTURY PHYSICS

The form of experimental research developed in the late 19th century was influential in structuring the experimental research of the 20th century. Experiments, which are based on careful theoretical analysis of instrumentation, but are still creative and imaginative, are found in works by many leading experimentalists of the 20th century; good examples are, for example, Kamerlingh-Onnes (Reif-Acherman 2004) and Millikan (van Fraassen 1980; Hacking 1983). The similar character of experiments also became the hallmark of large institutionalised laboratories such as the Cavendish laboratory, Cambridge (Kim 2002), the Physikalisch-Technische Reichanstalt, Berlin (Heidelberger 1998) and the Ryerson Physical laboratory, Chicago (Hacking 1983). These institutions and other similar ones have provided much of the basic education of leading experimentalists and have taught physicists how and why experiments are done.

From the late 19th century onwards, physics became more involved with microscopic phenomena. The entities of interest – atoms, electrons and photons – were farther removed from what was readily observed. Consequently, a development took place, which emphasised consequential justification. However, the generative use of experiments is still clear in the experimental style of J.J. Thomson (Kim 2002). It can also be recognized in many other experiments carried out in the Cavendish laboratory at the beginning of the 20th century, and also in Rutherford's way of using experiments (Kim 2002; Hon 2003). With advances in experimental techniques and the development of quantum theory, however, the situation changed and the reports and publications show indeed that the 20th-century physicists do not like to present their results in form of generative justification. This is also reflected in the 20th-century philosophy of science, where consequential justification is the dominant conception (Hacking 1983; Gooding et al. 1993; Nickles 1993).

In searching for generative justification and its traces in the 20th-century physics, attention must be paid now to the whole set of experiments, and not to single experiments only. In addition to this, the experimental details are of importance, with regard to notions about what has been required, in practice, to produce the reported results (Hacking 1983; Galison 1997). Under such scrutiny, there are many experiments, in which characteristic aspects of generative justification are indeed discovered; the experiments alter the theory within which they are interpreted, until an 'adequate closure is found' (Nickles 1993). As Hacking (1983, p. 56) has noted, there is not only growth and the accumulation of knowledge but also growth and the accumulation of methods. *The old methodologies do not vanish, but instead they are incorporated as part of a growing structure of a variety of methodologies.* We have thus good reasons to believe, as Nickles (1993) suggests, that generative justification of knowledge has been the authentic methodology in the production of knowledge and construction of theory in the 19th-century physics, and has never been actually abandoned; it is still relevant in the practices of modern experimental physics.

5. Generative Experimentality: A Suggestion for Epistemological Reconstruction

The physics taught in school and in introductory university courses is, for the most parts, a product of the 19th century and was then given its present form. There are thus all reasons to believe that a suitable basis for the epistemological role of experiments in teaching physics must draw insight from *the history and philosophy of physics* of that era. However, it is not a good idea to copy historical experiments, because the school's science is not the scientist's science; rather, didactical reconstructions are needed instead (Nersessian 1995; Izquierdo-Aymerich & Adúriz-Bravo 2003). The epistemological reconstruction of the role of experiments in physics, which is suitable for pedagogical and didactical purposes, and which makes experiments meaningful for students, should fulfil, in addition to the *educational goals,* also the two *epistemological goals* discussed in Section 2. The epistemological reconstruction fulfilling these requirements can be based on experiments in the form of the generative justification of knowledge. In what follows, we develop here the reconstruction on this basis and show how the philosophical premises P1–P6 discussed in Section 3 guide its construction.

The epistemological reconstruction of the role of experiments in the generative justification of knowledge is called here *generative experimentality*. It can be scaffolded conveniently using the traditional scheme based on hierarchical abstraction levels of knowledge as it is conceived in the RV (requirement P1 in Section 3). This scheme consisting of levels of qualities (I), quantities and laws (II), and theory (III) is outlined in Table I. By this means, we can describe the generative knowledge formation taking place in repeated steps of the description of observed facts, hypothesis generation based on interpreted experiments, and finally, empirical testing of the hypothesis. The epistemological requirements P1–P6 recognized in Section 3 are denoted in Table I, the stratified structure P2 is reflected in its three level structure. This scheme satisfies the requirements for an organizing structure and provides the possibility to discuss the process of knowledge formation within this structure.

The scheme outlined in Table I has many features found in the physics of the 19th century and as represented by e.g. the thinking of Helmholtz (Jurkowitz 2002; von Helmholtz 1886/1995). In addition, it contains aspects to be found from Whewell's conceptions of logic of discovery, as well as aspects reflected in Duhem's philosophy of science. From this perspective,

Table I. Three levels of conceptualization and abstraction

Level	Description	Uses of experiments
I Qualities	Conceptualisation starts from events of nature by recognition of phenomena (P3). Qualitative properties of phenomena and entities are formed by *classification*	Observations, experimentation and qualitative experiments. Experimentality have investigative and exploratory character (P3)
II Quantities and laws	Qualities and their mutual correlations suggest interesting quantitative properties. Qualitative dependencies are transformed to *quantities and laws* (P4, P5)	Quantitative experiments and designed 'precision measurement' are used in generative form. *Experiment is an interpretation of theory* (P5, P6)
III Theory	Generalisations are proposed and annexed to theory. Theory guides experimentation (P3, P5, P6). Generation of 'existence claims' of new phenomena, entities and their properties (P6, P1)	Quantitative experiments are in a role of *consequential justification.* Experiments test the validity of predictions and existence claims (P1)

our scheme is somewhat commonplace and not very novel, but it provides a scaffolding, which supports the guided construction of knowledge. As such, we think it compares favourably with other suggestions put forward in the science education literature and thus serves as a promising tool for the support of learning.

Generative experimentality starts always from qualities and produces quantities from qualities. Experiments then assign empirical meaning to quantities and laws (compare with Duhem 1914/1954 on quantities and qualities, with Hanson 1958 and Nersessian 1984 on empirical meanings). The sequences, which belong to generative experimentality, are schematically shown in Figure 1a. Briefly, the steps from A to C represent the experiments in the phase of discovery (context of discovery), and step D is the phase of consequential justification (context of justification). Generative experimentality is thus quite different from the simplistic, one-directional inductive scheme, shown in Figure 1b for comparison, and it also differs from the straightforward verificatory sequence shown in Figure 1c.

Step **A** of generative experimentality shown in Figure 1a is a sequence, where certain aspects of natural events suggest that they can be discussed

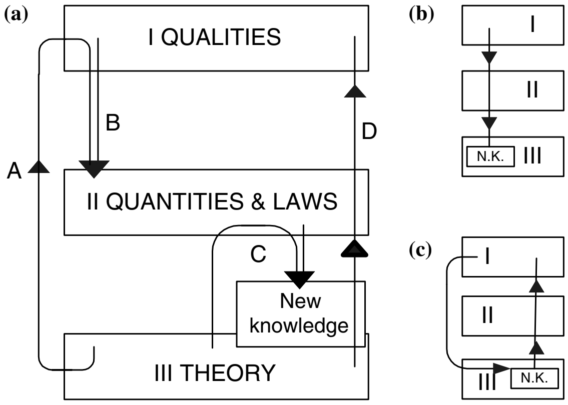

Figure 1. The sequences of production of new knowledge according to (a) generative experimentality. For comparison, the simplistic (b) inductive and (c) consequential sequences are shown. The piece of new knowledge annexed to the theory is denoted by N.K.

within the framework of some known theory, which then acts as a basis for isolating the phenomena for closer study (recognizing a phenomenon requires theory). The final stage of A involves figuring out the pertinent qualitative dependencies for further study.

Step **B** involves designing and planning quantitative experiments with the purpose to transform the interesting qualities to quantities, and the important qualitative dependencies to quantitative laws. Here experiment is interpretation of theory (see P4 and P5). Then, experiments are carried out. First, by changing the experimental setup, the 'phenomenon is stabilized' (or experiments 'create the phenomena', Hacking 1983; Buchwald 1994). Second, through repeated cycles the authenticity of phenomenon and its relevance with respect to natural events is evaluated (see P4–P6).

Step **C** extends the region of validity of the theory, which was the starting point of experimental design and interpretation. In this process, the quantities or laws are taken as generalized or idealized representations and they are annexed to theory as a new piece of knowledge. This leads to an augmented set of quantities and laws – *new knowledge* (box N.K. in Figure 1) – and ultimately, to extended theory with a wider range of applicability than initially. Reorganizations of theory may also be necessary. In this way, generative experiments affect the structure of theory and transform it. This part fulfils the requirements P5–P6, and parallels with empiricism.

Step **D** is for the consequential justification and for verifying experiments to test the new augmented theory. It is essential that new predictions are successful in situations corresponding to a wider area of phenomena or that different phenomena are involved (P1 and P6).

In the generative scheme, representation of empirical facts is of central interest; theory is seen as the effective classification and means of organization of dependencies revealed in experiments. This has the advantage that the distance between concepts and laws from observations is narrowed. Although the epistemological reconstruction is a gross simplification, physicists (as we believe) will find it familiar because it is designed to reflect the methodology of physics, as it is encountered in the history of physics. In teaching physics, this gives an authentic enough picture of the structure of knowledge and the processes for producing it.

6. Applications of the Epistemological Reconstruction and Learning Results

The reconstruction presented above has been used as a 'philosophical' basis in a course, *Conceptual Foundations of Physics* (CFP, one-year, in three parts, together 15 ECTS), for student teachers in the Department of Physical Sciences, University of Helsinki (Koponen et al. 2004). It has also been used in a somewhat modified form in the planning of laboratory works for school teaching (Koponen et al. 2004; Lavonen et al. 2004). Consequently, 2001–2004 the epistemological reconstruction based on the generative role of experiments has been used in several concrete cases in different exercises, for example in illustrating the formation of concepts and in the production of laws. An example of the teaching sequence based on the reconstruction, in the case of the induction law, is outlined in Table II. Typically, the teaching sequence was divided between different levels as annotated in Table II.

The educational goals discussed in Section 2 are reflected in the way the teaching sequence is designed. During this sequence, students work in small groups and are encouraged to participate in discussions, concerning how to conceive of the pertinent phenomena. They are also guided to discuss the adequacy of the experiments, the validity of their results and the experiments' relevance with respect to the phenomena under study. In order to evaluate whether or not the educational goals and epistemological goals are reached, we have gathered three types of evidence: written feedback, students' study reports, and associated modified concept maps.

6.1. LEARNING TO CONSTRUCT CONCEPTS AND LAWS

In tasks, where the meaning of concepts and laws was constructed, students were asked to represent how some well-known concepts are developed and what kind of experiments are needed to establish their meaning. Two concepts were chosen as examples: temperature and resistivity. In addition to these, two laws – Ohm's II law and Faraday's and Henry's induction law – were chosen. The teaching sequence consisted typically of a 90-minute lecture about the structure of the theory and processes to produce knowledge (based

Table II. Teaching sequence of the induction law (duration is 90 min)

Level	Experiments	Interpretations
I Qualities (30 min)	Qualitative observations with magnets, solenoids and coils. Correlations between currents in solenoid and induced voltage in coil suggest experiments with two coils	Movement of bar magnet produces current in nearby coil. Changes in current in solenoid produces similar effects → *induction phenomenon is recognized*
II Quantities and laws (40 min)	Experiment with two coils A (primary) and B (secondary) is designed. Precise measurements (MBL) are done with changing current in coil A and induced voltage in coil B. Behaviour of system is analysed using known theory (Ampere's law, Biot and Savart law, quantities magnetic flux density and flux introduced)	Correlation between the rate of change of current in A and induced voltage in B is represented graphically. Results are interpreted by using magnetic flux density and flux. Linear invariance is produced between rate of change of flux and induced voltage → *tentative induction law*
III Theory (20 min)	Generalizations: general induction law is proposed. New experiments are designed with different geometries and situations (number of turns in coil is varied, its position is varied, different rate of changes in current are used)	Predictions based on the induction law are tested. With their success, generality of the result is established → *new general law is established.* Position of new law in theory is scrutinized

on the reconstruction) and exercises (90 min each) following the lectures. The maps and written reports produced by the students during the teaching sequence were analysed qualitatively, in order to evaluate the epistemological role of experiments reflected in these maps and reports. Coding schemes based on attributes listed in Table I were used to detect the different roles of experiments. Interviews were used to confirm the correct interpretation of students' representations.

Most students constructed the meaning of temperature successfully. From the students' representations it was possible to distinguish the three levels of abstraction given in Table I. In level I, temperature was connected to the experience of warmness, qualitative observations of changes of state (melting, freezing, evaporation), in II to thermal expansion of liquids (liquid thermometer scale) and then to empirical gas laws to establish the gas thermometer scale and absolute temperature. The ideal gas law and notion of absolute temperature were discussed in level III. Experiments are discussed in the generative role in 93% of the responses, as indicated in Table III.

The concept of resistivity was discussed in the context of Ohm's II law and in this case students produced written explanations, which were gathered and analysed. The concept of resistivity proved to be somewhat more demanding than temperature, partially perhaps due to the choice to discuss it simultaneously with Ohm's II law. Now only 74% of students presented the experiments in a generative role and 10% introduced Ohm's II law as the basis of theory or just stated it and introduced experiments in the role of verifying the results, i.e. in the consequential role.

The construction of the meaning of physical laws was studied by using Ohm's II law and the induction law (Faraday's and Henry's law). The role of experimentality in establishing these laws is in principle rather similar, but there are conceptually significant differences between them. In Ohm's II law, magnitudes of quantities are related to each other, in the induction law, the time rate of change of quantity is related to other quantity's value. In the case of the induction law, the steps explained in Table II were discussed and students were guided to pay attention to them.

In both cases, students started with qualitative observations (stage I) and then progressed through stages II and III. Constructing Ohm's II law resulted in rather good illustrations about 'quantitative experiments' with experiments seen in a generative role in 74% of the cases (the same as in the case of resistivity, because these tasks were treated together). The induction law turned out to be more demanding and not all groups completed it successfully. In the best representations, the construction of the induction law was discussed much along the lines shown in Table II, and the role of experiments was generative in 63% of all cases, as indicated in Table III. In these reports, variations of the basic experiment were suggested to make the generality of the law plausible and to test the tentative law, in accordance with the consequential testing phase.

Table III. Role of experiments used by student teachers in learning concepts and laws. Relative fractions in each class are given (number of students is in parenthesis)

Concept/law	Generative	Consequential	Inductive	Undefined
Temperature	93% (13)	–	–	7% (1)
Resistivity and Ohm's II Law	74% (37)	10% (5)	–	16% (8)
Induction Law	63% (24)	5% (2)	8% (3)	24% (9)

The results discussed here indicate that by using the reconstruction, student teachers manage to better organize their knowledge about physics concepts and laws. The large percentage of students opting for the generative role of experiments demonstrates that students have learned to recognise the role of experiments in conceptualisation. This suggests that the educational and epistemological goals set for the teaching sequence are reached satisfactorily.

6.2. LEARNING TO PLAN LABORATORY WORKS FOR SCHOOL

The Department of Physical Sciences regularly runs a teacher laboratory course: Experiments in the School Laboratory (ESL, 10 ECTS), which is for the purpose of practical planning and designing of school experiments. In ESL, microcomputer-based laboratories (MBL) are used extensively. Students plan and implement a set of experiments on 5–10 specified subject areas (mechanics, electricity and magnetism, heat and energy, waves and optics, and modern physics). In the planning of experiments, generative experimentality is used in appropriately modified form. Learning during the course is thus focused on procedural understanding (e.g. decisions that must be made about what and how to measure and how to present measured data).

In ESL the plans, designing and implementation of experiments is done in small study groups. In project plans, concept maps are used and the evaluation of plans is partially based on these maps. After the approval of a project plan composed by the study group, the experiments are conducted as an investigation of their utility. Ultimately, the group produces a report on the task, including a presentation of the experiments, along with descriptions of their intended use in classroom teaching. The degree of success in applying experiments on the generative role is evaluated by using a five-grade scale from excellent to failed (see Table IV). Other aspects evaluated are: the

Table IV. Evaluation of characteristics of experiments used by student teachers in planning laboratory works. Relative fractions are for sample of $N = 109$.

Characteristics	Excellent (%)	Good (%)	Fair (%)	Poor (%)	Failed (%)
Degree of generativity	32	52	14	1	1
Realization of experiments	11	40	36	13	–
Qualitative meaning	15	55	23	4	3
Quantitative design	15	45	37	3	–

possibility to realize the experiments in practice (instrumentation, design and technical aspects), the support the experiments give for qualitative understanding of concepts (based on criteria in Table I at the level I) and the quantitative design (Table I, level II). The results of the evaluations from 2001 to 2004 for $N = 109$ students are shown in Table IV.

From the results shown in Table IV it is seen that the laboratory course produces good results with respect to practical possibilities to realize and implement the experiments in school context, and this correlates well with the degree of generativity of the planned experiments. The support that the experiments give for constructing qualitative meanings of concepts and the quantitative design of the experiments correlate also well with the degree of their generativity. These results indicate that generative experimentality leads to the desired expertise in planning the school experiments.

7. Discussion and conclusions

The motivation behind the present study is the notion that the existing views on the role of experiments in physics education are often unnecessarily limited and too narrowly scoped. For example, in traditional textbooks, there is the emphasis on experiments in the role of consequential justification. On the other hand, many suggestions to improve teaching utilize educational experiments, which more or less set the epistemological questions aside in favour of student-centred teaching. Nevertheless, the virtue of educational experiments, which are designed in the framework of 'personal constructivism', is that the student as starting point of teaching is taken better into account. There exists teaching models within personal constructivism, which also pay proper attention to the role of experiments in physics in general, but there still seems to be a need to make more definite the epistemological goals of such experiments.

The historical analysis of experiments in the 19th-century physics, which we have outlined here, has the goal to furnish a background for an alternative suggestion, which opens up a way to attend to the epistemology of experiments as a source of new knowledge and which takes into account the important aspects for learning. We suggest here an educationally oriented reconstruction, which is meant to bring back in physics education the neglected epistemological dimension of experiments; their use in generative justification. Generative justification of knowledge acknowledges the possibility that, to a large degree, theory and theorizing can be based on experiments. In generative experimentality the methodology of quantitative experiment have a central role. Attending to methodology and quantitative features are, in some respects, opposed to educational experiments since they are not always simple, and they are not designed in the first place from the point of view of students (e.g. designed to challenge their preconceptions). Such experiments can, nevertheless, be used to help students' conceptualisation in support of learning. Students can still have the satisfaction of participating in creating the knowledge for themselves although it now becomes strongly guided by the teacher and constrained by empirical observations.

In summary, the reconstruction, which we have developed by drawing insight from physics' history and philosophy, helps to eliminate the epistemological pitfalls of simple inductivism or narrowly scoped verificatory use of experiments. The generative view makes it possible to retain those aspects of experiments, which make them purposeful for learning by giving a starting point for students' own construction of knowledge during the learning process. The reconstruction helps also to conceive the experiments in their correct historical role and it brings back in teaching the generative use of experiments which, after all, has never vanished from the practice of physics.

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