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Unified View of Science and Technology for Education: Technoscience and Technoscience Education

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Abstract Science and technology education, both as distinct and integrated subjects, relies on a traditional conception of science and technology as quite different and separated enterprises. A closer look at the scientific progress, however, reveals the traditional view as being one-sided. This study scrutinises the unification of science and technology education from the viewpoint of recent studies, which have revealed an unexpectedly deep bi-directional relationship between the development of science and technology. The highly cognitive role of technology in scientific knowledge construction through experimentation reveals the need for a new unifying view, *technoscience*, and its consideration within science education. Since *technoscience* promotes a scientifically sound and authentic view on the relationship between science and technology, it increases the coherence of learning processes by combining these elements, which have been traditionally separated within education. Additionally, *technoscience* supports in a natural way the teaching solutions, which put weight on personal conceptualization for learning.

1 Introduction

In science education, scientifically sound and authentic content is naturally the necessary starting point. In addition, science education should be personally meaningful and intelligible to the students. It should not only have an intrinsic coherence and unity as a subject, but also retain this coherence and unity throughout the personal learning process. According to many contemporary social and personal constructivist views on education, at best, the learning process constitutes a dimension of progress, which runs parallel to progress in science itself (see Fensham et al. 1995; Nola 1998; Matthews 1994; Millar and Driver 1987). These features can be improved by using the philosophy and history of science to support the design of didactic solutions (for examples, see Hodson 1986; Layton 1993; Matthews 1994). Consequently, in this study the unification of science and technology education is scrutinised

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from the viewpoint of recent philosophical and historical analysis of the actual activities and practices of science and scientists (e.g., Chang 2004; Ihde 1979; Kroes 2003; Rothbart 2003). This kind of scrutiny reveals the connections between scientific progress, in the development of conceptual and theoretical structures and the material resources available for experimentation and instrumentation. Finally, this bi-directional relation between science and technology reveals a need for unified views, where the essential interdependence of science and technology is appropriately acknowledged, but where technology acquires a crucial role in scientific progress. For this type of new unified view, the term *technoscience* has been suggested e.g. by Latour (1987).[1] The notion of *technoscience* seems to be appropriate, because it embraces both the science and technology aspects of contemporary scientific activity.

The present views on *technoscience* broadly take into account the social, economic and ethical aspects, but its epistemological dimension needs to be extended. The earliest studies on the relationship between science and technology come mostly from the social studies of science and technology, which reduce them to the social dimension. In the social literature the term *technoscience* is frequently used to refer to the hybrid resulting from the fusion of science and industry. Recently, philosophical and historical studies of science have increasingly paid attention to experimentation and, in consequence, they have highlighted the dialectic between the history and philosophy of science and the history and philosophy of technology in the context of embodiment of science in experimental technology. In fact, paying attention to the role of experiments and instrumentation, i.e. experimental technology, is not so recent a trend. Already Duhem (1914) presented insightful views on the essential role of instruments and apparatuses—from a more recent viewpoint scientific experimental technology—in the experimental processes of physics. In fact, many of Duhem's ideas seem to come close to the more recent picture, where *technoscience* is appropriately augmented to take into account the epistemological aspects of measurement and experimental technology.

Basically, science and technology studies have discussed two trajectories of the science–technology relationship: science-driven technology, in which "pure" science is thought to be "applied" to practical solutions, and technology-driven science. At a concrete level it is unquestionable that parts of our physical world are instrumentally and technologically revealed and vice versa: technological development is frequently improved by scientific work. However, the role of technology at higher levels of scientific theorising is often times not as apparent, and not many philosophers have focused on this question. One exception is Heidegger (1927), who extends the idea of technology-driven science probably most radically, by holding that what we take to be science, even at its most theoretical heart, is an effect of a technological way of taking things, of "revealing a World" technologically. While the relationship between science and technology is studied in this article in the context of the practices of science, the dialogical tension between these two trajectories—that of science-driven technology and technology-driven science—is considered to be a *primus motor* of scientific progress for the most part of physics, as well as a part of engineering

[1] Latour's (1987) concept of *technoscience* encompasses the expanding and overlapping domains of technology and science; he uses the world *technoscience* to describe all the elements tied to scientific contents, no matter how unexpected or foreign they seem (p. 174). He thinks that scientific view to "Nature" is purely socially produced and thus perceives *technoscience* as the writing of expanding networks of *technoscientific* data production, consumption, and distribution (p. 250). The view considered here, in any case, perceives science from the perspective of working physicists, as reaching for something (at least partly) extrinsic to the personal interests and power structures of actors, called "knowledge of the physical world". In addition to Latour's view, epistemological aspects are here emphasised.

research, but in some areas it is more visible than in others. Nowadays, it is apparent that "Big Science"—as, for example, high energy physics—is so closely tied to "Big Technology" that one can meaningfully speak of a single, complex phenomenon which is at the same time science, scientific technology and technological science: *technoscience*. Moreover, "Big Science" is quite technology driven, while pure science and technology are nearly inseparable. Large research groups are involved with scientific design and testing of experimental machines, accelerators and detectors (see Baird 2004; Galison and Thompson 1999). For example, consider the invention and development of particle detectors such as the multiwire proportional chamber, developed by George Charpak for which he received the Nobel Prize in 1992.[2] Also in nanoscience it is impossible to say where physics changes to technology, as in case of Albert Fert and Peter Grünberg's discovery of Giant Magnetoresistance (Nobel Prize 2007) or Gerd Binnig and Heinrich Rohrer's work on scanning tunnelling microscopes (Nobel Prize 1986). Similar examples can be found in diverse areas of applied physics, on soft and hard condensed matter where pure science is motivated by and merged to technological research. Naturally, in physics there are fields of research where the primary objective is in responding to the fundamental questions concerning the nature and relations between time, matter and space. In technology, including engineering technology, there exists a variety of aims and fields which, as such, are less scientific than those mentioned, or (in terms of their scope and outcomes) not scientific at all. This article, however, focuses on scientific theorizing through experimentation in physics and shows that there is a vast area where pure science and technology overlap, and just how the ideas of *technoscience* are realised in this area.

The main notion considered in the present work is that the *technoscientific* view has not yet been implemented as the basis for an intrinsically (i.e., from a practising physicist's viewpoint) unified science and technology education,[3] but there are advantages in doing so. It is suggested that there is a clear need for such a rationalisation of views in education, and that it is by now time to discuss the benefits of such a view also in the field of science education. In what follows, this topic is discussed in the more limited contexts of physics and physics education, where the ideas of *technoscience* are perhaps most easily supported.

2 Experimentation as Epistemological Core of Technoscience

Technology is merged to physics primarily through experimentation. According to the views held for most 20th century philosophy, experiments are for testing scientific theories. In this case, the experiments are used in the role of what can be called—following Thomas Nickles (1989)—the consequential justification of knowledge. In fact most of 20th-century philosophy has been dominated by a distinction between logic of justification and

[2] A large amount of work awarded the Nobel Prize is apparently technologically motivated and maintains a strong hold on the field of *technoscience*. Along these lines, consider also John L. Hall and Theodor W. Hänsch's contribution to the development of laser-based precision spectroscopy (2005), including the optical frequency comb technique and Alexei A. Abrikosov, Vitaly L. Ginzburg and Anthony J. Leggett's pioneering contributions to the theory of superconductors and superfluids (2003).

[3] The viewpoint of social studies has already attracted attention in education, which concentrates on the social and humane nature of science and thus aims to teach about science in relation to the society (e.g., STS and STSE—education, see also Rudolph 2005). In order to improve learning about science itself and conceptual understanding of science, we need to narrow the focus to physics. Nevertheless, the extrinsic views of social studies (Mitcham 1994) does not conflict with the here-presented intrinsic view (i.e., a practising physicist's viewpoint), but rather supports it, because both emphasise the social and humane nature of science.

discovery, which in philosophy become formalised by Reichenbach (1938). However, discovery and knowledge generation was seen as a major and integral motive behind experimentation in many 19th-century philosophies, like in Whewell's (1840) philosophy of science as well as in Pierre Duhem's (1914) views on science. The more recent philosophy of science (e.g. Baird 2004; Chang 2004; Franklin 1986; Galison and Assmus 1989; Keller 2003; Kroes 2003; Nickles 1989; Woodward 2003) has rediscovered the role of experiments in generating knowledge and brought these aspects under closer scrutiny. This kind of construction and justification process, which transport both experimental and theoretical results, Nickles (1989) refers to as a generative view of knowledge production.

Examining the practices of working scientists provides evidence that both the consequential and generative scheme are true: whichever approach is used depends on the phase or stage of the work in progress. Of importance here is that, in both views, the relationship of the scientific experiments to theory is in the focus. Experimentation is used by a scientist as a means to actively interfere with the material world, in order to acquire knowledge, which is then used to support the more hypothetical generalizations. If these generalizations can be used as a basis of successful predictions, through consequential justification, the circle is then closed and new knowledge is acquired. It is this type of conception of experiments which lies at the core of the *technoscientific* view developed here. Moreover, it differs in important respects from existing established views, but by the same token it also borrows from and synthesises many existing ideas and notions. Therefore, a short resume of the views finding their way in this discussion is presented in the following.

2.1 Theorizing Through Experimentation as Constructing of Material and Conceptual Models

In model-based views on science like in Ronald Giere's (1988, 1999) and Van Fraassen's (1980) views, knowledge is mainly understood to be expressible by way of words, symbols or as conceptual abstractions. According to these conceptions, the hierarchy of conceptual models constitutes the theoretical knowledge (see Giere 1988). Theoretical knowledge, in turn, becomes developed in mutual interaction between models at different levels. The lowest level of the system of models suggested by Giere (1988) constitutes visual models. From the viewpoint of models, the epistemological significance of technology becomes more apparent, if we went further. Namely, experimental set-ups and devices can be seen as the concrete material models, which carry the "thing knowledge" (Baird 2004)—knowledge about designs, materials and practical conditions needed to complete successful experiments.

The advantage of the material models is that they can be manipulated materially and thus they provide a different entry to the world than conceptual and visual models. Apparent examples of such scientific material models are the "ball and stick" models of chemistry and Watson's and Crick's DNA model, which embody the knowledge extracted both from experimental results and theory, but in fact every laboratory phenomena can be seen as a kind of model of something outside the laboratory (this notion is discussed in more detail in Sects. 4.2 and 4.3). Also the machines used to construct the phenomena or conditions in the experimental system, such as Robert Boyles's air pump, cyclotrons and particle accelerators, can be seen as types of material models of both functional and structural ideas and principles underlining the system (see Sects. 3 and 4.1). In addition, also measurement instruments can be considered as material models, which have the ability to control the material (theoretically expected) values of measurements (see Sects. 4.4 and 4.5).

The development of the material models is tied to our capacity to construct, control and manipulate "the world in laboratories" and thus the knowledge embodied in material models is at least partly technological, including the knowledge that Davis Baird (2004) calls "working knowledge". Without the material models physicists have no access to the world; it is through the material models the concepts of theories get empirical meanings.

The conceptual and material models become developed in mutual interaction, and closure is achieved when they fit together adequately. It is just this end result Van Fraassen refers to as "empirical adequacy" and Giere refers to as "similarity". However, there remains a question, when we are satisfied that such closure is achieved. In many cases just this problem is at the core of scientific disputes and controversies. The problem seems to be that there is no objective, sociologically neutral or unambiguous method to settle this question (see e.g. Nola 1999). Rather, any methodology which manages to demonstrate control over phenomena, the ability to intervene and manipulate or capabilities for creating phenomena by using technological devices becomes accepted, as will be discussed more closely in Sects. 4.1 and 4.5. In this process, social aspects cannot be simply bypassed—epistemology becomes intertwined with sociology.

2.2 Social Aspects in Accepting Scientific Knowledge

Theories are brought in line with our cognitive structures and shared scientific understanding of the success of current scientific theories. In addition to logical or epistemological and material dimensions, the construction and justification process (methodology) has both social and psychological aspects. Therefore, the scientific process is one that involves not only individual minds, but also essentially involves the collective. Thus, in the process of acceptance of knowledge, the Kuhnian idea seems to hold; there is no standard higher than the assent of the relevant community[4] (Kuhn 1962, p. 94). The decisions of relevant communities are not necessarily correct; nevertheless, that is the court which judges, whether the research questions and methodology are relevant or not. Without such a community structure, the justification process would result in endless regression without coming to any conclusive views (see Collins 1985; Nickles 1989; cf. MacKenzie 1989).

The recent views by, for example, Collins (1985) and Latour (1987), have revealed the importance of social factors in knowledge creation, which rather undermine than support the justification process. According to these views experimental accounts are believed and become authoritative through social institutional power. In this case, the technical knowledge and standards on which the experiments rest are seen as pure functions of the social power of the group performing them. Such a function transforms laboratory apparatus and instrumental techniques into rhetorical devices rather than a means to study the actual states and events of the physical world. For example, for Latour (1987), the experimental success has nothing to do with accessing nature's real structures or capacities. Simply, the idea of nature is invoked by the winner of the controversies, and the winner imposes the rules of future research of "the phenomena". In this extreme, where the defence has no other basis than social and cultural negotiation, Nature plays no role in the process. As Latour (1987) puts it "we can never use the outcome—Nature—to explain how

[4] There are different views of what the community is, and what aims and views the individuals of the community need to share in order to be counted as members of the community. Many Kuhnian and post-Kuhnian philosophers refer to 'the scientific community' as a group of equal experts who somehow reach consensus and who take part in defining the truth within that community (see Kuhn 1962; Latour 1987). Many others, who study the practices of science (e.g. Van Fraasen 1980; Nickles 1989; Hacking 1983; Harré 2003) see "the scientific community" as a heterogeneous group of practitioners, who may have different views, but have a shared objective.

and why the controversy has been settled" (p. 364). Although scientists do not share this outlook (see Newton 1998), this extreme view nevertheless seems to have something to say about the ways in which scientific truths become established and winners of the truth are awarded (see Friedman 2001).

There are also other more moderate views, which see the bearing of the social dimension on epistemology as being more positive, as supporting the processes of science (e.g. Hacking 1983; Nickles 1989; Rothbart 2007). They acknowledge the rather indisputable fact that the scientific inquiry is a social process and the reasoned judgement is itself socially defined. Therefore, it is natural and necessary that the logic of science has a certain social background, but no primary role needs to be attached to sociology, and reducing science to sociology would be an absurd exaggeration. On the other hand, science is not seen as the monologue of a unanimous community possessing objective knowledge. This kind of moderated sociological view serves as a valuable guide to understanding the social background of scientific research and technology, which retains both as being recognizable to their practitioners. It is this moderated view which is adopted here as a basis of the *technoscientific* justification processes. The social nature is considered only to the extent, in which it bears on epistemology, as supporting the progress of science.

2.3 Engineering and Experimental Knowledge

Engineering philosophy of engineering and technology[5] is oriented toward the technological manner of "being-in-the-world". Within such an orientation, the technological process is described by four "ends": design, construction, implementation and manufacturing (Mitcham 1994; Vincenti 1990). Of these ends, design is considered to be a central mission of engineering. In addition to producing material and non-material artefacts, the technological process, especially the engineering work, aims also at a special engineering knowledge. In this way, design constitutes the cognitive bridge that crosses a spectrum from abstract, idealized conceptions to concrete, highly complex products of technology existing in the real world.

Moreover, design does not (necessarily) require hands-on working. Rather, it is seen as the evolution of the functional device, which can be tested and judged in a symbolic world, through different kinds of thought experiments (see Rothbart 2007). However, development of the material knowledge connected to design processes makes sure that the symbolical meanings can be and are translated into concrete experiences of manipulating the material world. The same applies to the design of experimental systems and instruments, since the design is essentially the means of scientists' "interventions" in the material world (in the sense Hacking (1983) describes it). The knowledge products of such design include both material knowledge and abstracted conceptual knowledge. Consequently, technological knowledge is either functional or descriptive and ranges from everyday knowledge to scientific modes of knowledge, called engineering knowledge. The engineering knowledge shares the same general form with the scientific theories—it is

[5] Philosophy of technology is in its infancy as an independent field of study. Philosophy of technology can be further divided into two fields, to engineering philosophy of technology and humanities philosophy of technology (Mitcham 1994), the former of which is employed here. Also the term "technology" is not well defined. Here, it is limited to the practices and the results of engineering as well as to the scientific research on engineering, because the focus of the article is on scientific theorizing through experimentation in physics. This is based naturally on the long traditions of skilled craftsmen, technicians and engineers at different levels, such as engineering scientists among other contributors.

hierarchical in nature[6]—and uses similar concepts as science (some examples are discussed by Vincenti 1990). In the experimental research of today, in which these modes of knowledge come into circulation and are developed, neither functional nor descriptive knowledge is privileged. A complete understanding of the tunnelling microscope, for example, requires both functional and structural descriptions (see Rothbart 2007), which at the same time are rooted in physics and technology.

These notions about the role of engineering fit quite nicely within Hacking's view of the importance of intervention. Simply, without the means of intervention, without a suitable device and machines, there is no prospect for demonstrating success. Very often, such devices for intervention are themselves quite complex and their operation is based on the principles of the scientific knowledge they are meant to advance. The use of such experimental devices and machines is part of the knowledge generation-justification cycle, where not only the new knowledge but also the reliability of machines through success in producing knowledge is established.

3 Physics as Science and Technoscience

The traditional view holds that technology creates new artificial things and science discovers, with the aid of the scientific method and instruments, what is already present in nature. As it should be now clear, on basis of aforementioned notions about the concept formation, scientific knowledge is not simply "discovered" from nature as obvious facts, but is painstakingly constructed through careful and well-planned experimentation and the accompanying interpretation of the experiments. In that process, the available technological knowledge and the activity that establishes the design of experimental setups and their manipulation for control are crucial. This tight relationship is nowhere seen so clearly than in physics, which provides many examples of such close connection and interdependence. Therefore, in what follows I will concentrate on physics.

The reality that physics opens up to us is accessed through the window of technology. Through experimental technology scientists gain access to the parts of nature that would otherwise remain hidden due to either human shortcomings or to contingent boundary conditions prevailing in our universe. On a concrete level, on the one hand, the capacities of technological capability lead to the productive capacities of experimental science, and, on the other hand, capacities are revealed by technological instruments. This is in contrast to a traditional or oversimplified empiricist view, where experimental technology is only seen as a means to collect new data from Nature; that is to say, once the new data has been produced, technology has played its part and the real, "hard" scientific work—theorising—may begin. It should be noted, that this kind of oversimplification and naïve empiricist conception is quite different and even hostile to the *technoscientific* view advocated here.

In modern laboratories we do not see scientists "observing" nature; indeed, not more so now than in experimental laboratories and institutions of the late 19th century and early

[6] For example, the following stages of engineering knowledge can be recognised: (1) technical know-how including sensorimotor skills or technemes, (2) functional rules or "rules of thumb" and structural rules, (3) technological laws and 4) technological theories (see Mitcham 1994; Vincenti 1990), in addition to which is required at least socio-technological understanding. This socio-technological understanding covers various elements of knowledge, regarding the relevant field which are involved and recombines these elements in interdisciplinary synthesis. Additionally, just like in science, there exists implicit, tacit engineering knowledge.

20th centuries (which established the more modern tradition of large-scale, well-planned experimentation). Instead we see them actively and intentionally creating and designing experimental settings, instruments and machines, which produce or isolate interesting phenomena, which do not exist outside the instruments and machines as such. Moreover, the experimental data are not collected by passive observations but detected by theory-laden instruments, the "in-built intention" (Ihde 1979), of which is to reduce and modify the complex phenomena to particular quantities. Hence, not only engineers create things (technical artefacts), but also experimental scientists create things: they create phenomena by using the scientific instruments of very special design towards that purpose (Hacking 1983). In this a way, science discovers through producing artefacts—material as well as conceptual, and they are both developed in mutual interaction. This, on the other hand, creates the knowledge of physics in a special form of quantities and laws, a very special product of experimental process made possible by the instruments and machines made for that purpose. It should be noted, that thinking forms of physical knowledge as conceptual artefacts and experimentally stabilized phenomena and devices, where they can exist as material artefacts, does not mean denying their value in understanding the physical world and making it more accessible to us.

In such a manner, technology modifies and affects physical knowledge. But what then, is physics about, if it is seen as constructed by studying laboratory phenomena? For example, what aspects of "natural" phenomena are we studying when we study the interaction between short-lived entities produced by particle accelerators? What do we "see" through an electron or scanning tunnelling microscope or sonic probing? Or what do we reach by employing human-made measurement instruments, such as thermometers and voltmeters, producing quantities, which are not properties of nature as such, but rather what have been called "phenomenological profiles" (Ihde 1979) of instruments? The question remains, if not among professionals, but certainly among students, educators and philosophers, as well as among laymen, what is such physics about? Through providing both scaffoldings and limits of physical reality accessible to us, technology also necessarily affects our conception of reality. Therefore, technology not only encompasses a methodological role in physics, but in addition an epistemological and cognitive role, even to the extent that it affects our ontological positions. Owing to these fundamental roles, technology should be an organic part of physics education.

Finally, as derived from the notions above, it follows that we need a new unifying view of technology and physics. This can be provided by *technoscience*, which acknowledges most physics as an amalgamation of science and technology. A product of *technoscience* is not only an understanding of nature and of its phenomena, but that also necessitates and provides the capability to create phenomena and design ways to control and manipulate them. By revealing physical reality and simultaneously producing it, *technoscientific* process embodies the dialectic between the two trajectories of the science–technology relationship: science-driven technology and technology-driven science. In such a view, technological devices and the phenomena they produce are also part of physical research and of scientific interest, and on the broader scale, also part of nature. The following section discusses the implications of these. Finally, Sect. 4 discusses how *technoscientific* viewpoints of physics outlined in this article can be used, in order to improve physics teaching and learning.

4 Reality Revealed through the Window of Technology

In science text-books, physics is introduced in form, which emphasises the structure of knowledge and, moreover, the reconstructed nature of its knowledge; knowledge as hierarchically organised concepts, laws and theories. Those abstract ideas cannot be directly compared with the "nature" these abstract ideas are meant to describe. For this purpose technology is needed to reach the cognitive goals of physics but, at the same time, it happens to be that the goals of technological advancement and progress of physics have merged. From the typical methodological point of view, technology is employed, for example, in order to overcome imperfections and limitations in human perception by providing measurement equipment, to standardise the modes of sensation in collecting data and to process the data. For physicists the scientific technology counts as more important; knowledge, techniques and material instrumentation (Mitcham 1994), on the other hand, constitute a bi-directional medium through which they draw their concepts of physical "reality" (Ihde 1979). In the experimentation of physics, the world is simultaneously written and read technologically (at least) in two senses. First, it is instrumentally revealed and even produced. Second, increasingly more scientific phenomena are clearly technologically produced and tailored. Even if we think of this viewpoint taking into account technology only as material objects, examples of the former run from telescopes, compound microscopes and electron microscopes to devices used in making the special laboratory environment for phenomena, such as Boyle's air pumps and their more advanced followers (nowadays, we have vacuum science), and to quantitative measurements enabling instruments, such as clocks, thermometers, the galvanometer, electrometers, all of which fall within the boundaries of physics-based metrological science (of its importance and close connection to physics, see Hänsch 2006). And a very special class of technological measuring devices is the sensor technology, with such advanced products like detectors in the Large Hadron Collider (LHC) in Cern.

4.1 Physics as Design

The structural understanding of relations, connections, and interactions of the physical world is the product of useful technology, the product of our capacity to control processes in experiments through intelligence. Therefore, the very success of the experimentation lies in the control and manipulation of material laboratory phenomena. In the heart of physical research is a skilful engineering of experiments. Historically, many successful experimenters have been skilful in practical work: During the 17th-century, the techniques and empirical approach of craftsmen and artisans found their way into the emerging experimental sciences. For example, Robert Hooke, who enjoyed a reputation as the foremost experimenter in 17th-century England, nurtured his experimental skills in machine shops as he immersed himself in the glass industry of Holland. Galileo built nearly one hundred compound-lens telescopes. Boyle freely admitted to his indebtedness to the practices of 'tradesmen'. Also Michael Faraday devoted much of his time to develop skills, which he himself emphasised. Naturally, the kinds of skills needed does change over time, but not the fact that the capacity to control material processes is the challenge of experimentation. Sometimes, however, practical invention gradually leads to theoretical analysis, an example of which is the improvement of the development of thermodynamics through a series of inventions in the steam engine: Newcomen's atmospheric engine (1709–15), Watt's condensing engine (1767–84), Trevithick's high-pressure engine (1798) and finally Sadi Carnot's ideal engine (1796–1832), the ideas of which were employed by Lord Kelvin in developing the understanding of absolute temperature (Chang 2004; Hacking 1983). Also in case of many older, ordinary specimens of technology and techniques, such as optics and "know-how" of complicated lens systems (or the system employing lever arms and the conception of strength and other statistical mechanics), it is not a relevant question to ask which one came first; indeed, the "know-how" and "know-that" are developed in mutual interaction. These kinds of skilled practices and judgemental behaviour are used as material arguments in the experimental reasoning of physics.

Nevertheless, in actual laboratories we find researchers not following a stepwise-sequenced, universally justified scientific method, as proposed in the traditional views, and as often displayed in science education. Instead, the different methods of scientific experimentation are developed and become frequently improved in the design of experiments, which develops itself in the course of the growth of science. *Technoscience* discussed here is for revealing how the central "method" of physics is, in practice, centred on scientific design, which aims, like engineering design, at a special kind of control over nature and to sharpen that control. Scientific design is a cyclic and iterative process, providing creative and critical planning and construction of material experiments and interpretations of the experiments, using and developing knowledge of experimental technology and scientifically designed experimental knowledge (see Fig. 1). The scientific design process intertwines intimately the development of science and technology—considered both as theories and as action. The confluence takes place at every level of scientific and technological theories (introduced in the Sect. 2).

Experimental knowing comes from understanding the functional role of ideas in the man-made material systems.[7] The material realisation of instruments, an experimental apparatus or system, is a kind of material model of the ideas the experimenter has of the "functioning" of the phenomena under study. To this is linked a large amount of technological knowledge, which is iteratively developed in the design process. Hence, finally, the scientific laws obtain upon the capacities of the experimental system: for example, in classical mechanics, repulsion, attraction, resistance, pressure and stress capacities are "observed" when the experiment is running properly (cf. Cartwright 1999). Furthermore, since ancient times, nature itself has been compared metaphorically to a machine. An experimental specimen or system is assumed to function as one of the world's machines with capacities to generate a "natural" change when sufficiently agitated (by a mediating

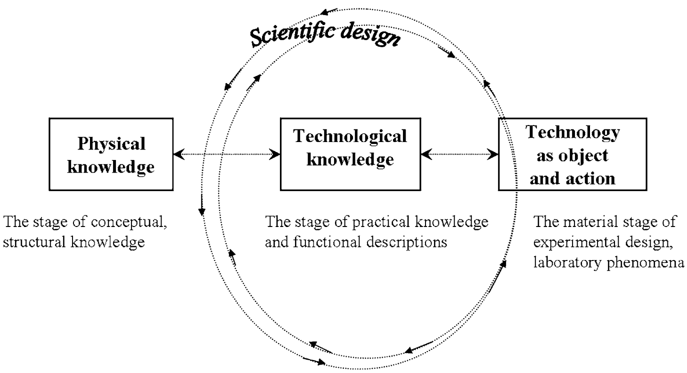

Fig. 1 Physical knowledge is constructed through scientific design

[7] This, however, is not to deny or suggest the other possible aspects of knowledge as being merely instrumental. Following the instrumental theory of Dewey (1916) all knowledge, even the most esoteric theoretical concepts from the most uncommon fields of research, has meaning only to the extent that it provides a means to some end. Indicated here is only the understanding of relations, connections, and interactions of the world as the source of useful technology, the source of our capacity to control processes in nature through intelligence.

experimental technology). This idea is most apparent in the development of laboratory phenomena in the tradition of mimetic experimentation in the 18th and 19th centuries. The development of Charles Thomson Rees Wilson's cloud chamber is a special example of this. Its primary purpose was to reproduce the phenomena of the Earth's atmosphere in a laboratory, in order to enable the study of meteorological optics and atmospheric electricity in the late 19th century, but it was developed further to particle detectors and apparatuses used in analytic matter theory among his Cavendish colleagues (see Galison and Assmus 1989). Hence, primarily, it demonstrated the functioning of meteorological phenomena, and later the same invention was used to improve the understanding of the interaction of elementary particles. Nowadays the data are increasingly produced through agitations, manipulations and inferences rather than through "observations". Consider, for example, differing methods of spectrometry including a signal (e.g. electromagnetic radiation) generator, detector, signal processor, and readout device, or scanning electron microscopes, field ion microscopes, and scanning tunnelling microscopes and so on (for further discussion, see Rothbart 2007).

In these experiments and experimentations of knowledge construction, abstract, often inaccurate, ideas and concepts describing "the world" are frequently defined and developed, by using and designing instruments, which have the purpose of making the concepts mutually measurable and materially controllable. These ideas are present in experimenters' skilful practices, communicated by a visual language and developed in design plans and experimental inquiry, which prepare scientists for action. Thus, the experimenters' epistemic ideas about knowledge inquiry, laden with meaning about idealised relationships between experimenters, instruments and laboratory phenomena in various conditions, can be read in design plans (see Rothbart 2003) and in laboratory notebooks. This design work aims to develop methods as well as individual claims, which finally become practically and socially justified: the justification of the designed experimental systems and instruments lies in the pragmatic, scientific determination that they work.[8] Consider for example the evolving understanding of "pressure" and "temperature", which took place in mutual interaction by the development of instruments such as thermoscopes, thermometers and barometers (Chang 2004; Middleton 1964).

The ability to control and make things happen by using "causal powers" of entities not directly accessible is quite apparent in the research on the level unattainable by our perception. In nanophysics and with nanolevel phenomena, there is no better way to secure that things are actually working as we would like them to than to wait and see whether the observable outcome fits our ideas of the supposed actions at the nanolevel: if the nanostructures under changing macroscopically controlled conditions behave as expected, that is, if the nanoconveyors and minimachines manage to cause expected macroscopic effects, then the entities behind these causes must be real. Consequently, the capacities of experimental systems give rise to the apparent regular behaviour of the "world" that we express by our physical laws (and instruments to the quantities by which they are described) and are thus worth becoming the object of closer scientific scrutiny.

4.2 What is Physical Knowledge About?

The phenomena under study are "created" in two senses: On the one hand, the materialisation of the experiment is the creation and manipulation of an apparatus producing or

[8] Because the experimental success is a product of skilful action of scientific design, it should rather be called the designer's success.

isolating phenomena and instruments reducing and modifying those to experimental data. On the other hand, the simultaneous conceptualisation of nature takes place in the mind of the intentional researcher by his or her own cognitive acts; it is neither produced by the object of manipulation, nor does it arise directly from the object of "Nature".[9] Should we then, facing the creative and intentional nature of knowledge construction, give up the traditional conception of physics as describing independent, constant features and causal regularities of "Nature"?

In full-fledged constructivism, such as that proposed by Latour (1987) and Janich (1978), this notion has led to views, according to which the experimental objects and processes are seen as nothing but artefacts of social construction, and science as a whole is thus seen as a branch of technology.[10] If the successful justification of knowledge is considered to be purely social, such knowledge has no value in understanding the physical world and making it more accessible to us, as was noted in Sect. 2.2. This kind of extending of the notion of technology (technological reality), and contracting the notion of science (scientific reality) in an unwarranted way to that of mere sociology, eviscerates both science and technology of its content. In the face of the strong influence of scientific and technological progress on our everyday lives, this influence has the capacity to change the world and make things happen, the attempt to reduce science and technology to sociology and power games should be refuted.

At the other extreme, we find views which are based on a strict separation between the natural and the artificial in experiments. Not even explicitly formulated, such views are often implicitly admitted in the traditional discussions of philosophy,[11] which have centred on the relation between theoretical descriptions and observational reports, and not around questioning the relation between the material practice of experimenting and the real world (for a detailed analysis, see Harré 1998). Nevertheless, this view is based on the assumption that it is always possible in experimental results to eliminate (at least nearly) all that is artificial and which might be due to the use of technology. This possibility motivates (or lures) us into thinking that the experimental statements can be taken as neutral descriptions of the world. However, this extreme view—no more than its sociological rival in the other extreme end—is supported by considering the practices of physics; indeed, physics itself cannot distinguish between the artefactual and the natural (Kroes 2003), since all the objects involved here are physical.

The critics of traditional views, like Latour (1987), are right in noting that scientific design does not take place in a purely logical-epistemological world; for example, the used methods have to be accepted by communities of researchers, fulfil the ethical conditions and financiers' expectations. Experiments are multidimensional manipulations, in which

[9] Compare Duhem's (1914) idea of the two kinds of instruments of physicists, the "mental" and "material" instruments.

[10] On this view, physical reality is interpreted as the outcome of a *technoscientific* practice, not as its object. Since the outcomes of scientific experimentation are taken to be pure social constructions; those are the results of negotiation processes between all actors involved. This way, also physical reality itself becomes a pure social construction and, thus, an artefact.

[11] This is characteristic, for example, of the traditional discussions between inductivists, such as John Stuart Mill and William Whewell, and fallibilists and provisionalists, such as Francis Bacon and Karl Popper. Both views see experimentation, including experimental systems and activities, as a pure means of producing particular empirical propositions by which the epistemic value of general, theoretical notions are to be assessed. Overall, most of the earlier approaches to epistemology of science describing "the growth of scientific knowledge" do not accommodate instruments but concentrate merely on changes in theory. Thus, for them, the instruments are a "transparent" means by which to produce the facts of nature.

the aim is to achieve a stable mutual adjustment of theory, discourse conventions, data collection and analysis and practical techniques. And the factors extrinsic to the process, such as the cultural moral and economical, make choices between the different research topics and methods even before the settlement on a research project. Hence, the kind of result reached through physical research depends on many things, including the state of technology, educational and political institutions and the economy. Nevertheless, as pointed out by thinkers putting weight on epistemology, it is not possible to explain the successful improvement of design on the basis of pure, socially constructed knowledge conditioned by structures and the interests of actors. Hence, the situation warrants seeking contextualised unifications of traditional views on the nature of science and technology, which perceive science and technology as quite different and separated enterprises; the former is seen as a school of universal knowing and the latter is seen as a school of doing.

Between these extreme views, there is plenty of room for more moderate and tenable views. For example, Rorty (1989) perceives science as a wholly discursive activity, like Latour (1987). Unlike Latour, who ends up arguing that Nature does not penetrate the walls of the laboratory, Rorty admits that the world causes us to entertain certain beliefs. He sees the cause of our beliefs not to be Nature, but Nature as domesticated in apparatuses and in laboratory phenomena. But also for Rorty, the statements such as how “physics fits the world” serve as an empty compliment. To some degree, it is a matter of taste in making such a division between the natural and artificial in physics because, after all, laboratory phenomena also occur in world and also in nature, if artefacts (and even humans) are taken to be a part of nature.[12] As such, features of experiments are not just discursive representations of the world (or nature) in a material medium, but they are aspects of the phenomena of the world (that is, natural phenomena). Moreover, the great use of laboratory phenomena is their ability to function as basic models which can be used to reduce complex real phenomena into analyzable and understandable parts.

Accepting these ideas, what we need to ask next is, if experimenters speak about artefacts of experimentation, what, then, do they refer to, if all are produced artificially in laboratories and are part of the world in the focus of physics? While experimenters speak about artificial data, as opposed to genuine data, they refer to results that are generated by an artificial environment or artificial means of “observation”, or the production of “natural” phenomena and objects under study. Typically, measuring instruments, machines producing phenomena and conditions under which phenomena are studied produce these kinds of artefacts. For example, early telescopes produced coloured fringes due to chromatic aberration. Additionally, physiological and psychological elements can interfere with creation of the phenomenon under study or, furthermore, with the reading of a measurement device. The use of a measurement instrument also necessarily impacts the state of the system, which sometimes blurs the result; for example, the thermometer employed in a measurement may cool down the object substantially.

In conclusion, the phenomena studied in physics, the conditions under which they are studied, the instruments used and the measurements taken are created (or constructed). Nevertheless, this does not imply subjectivism or relativism. After all, experiments can neither create anything experimenters can image nor can the experimenter make the entities and species of the world that are captured in a laboratory behave according to his or her own will (cf. Hacking 1983). In as much as experimenters cannot create phenomena and develop instruments according to their own free will, they experience all kinds of

[12] Finally, modern physics lacks the clear traditional conception of the world, which is composed of objects with certain intrinsic properties and interactions between those objects.

constraints when intervening in the world: technological, economical, political, ethical, and social—among other constraints, which are linked to us as human beings—that change over time. But the natural constraints differ from technological constraints in an essential way that they cannot overcome. The motivational view of physical research (Fine 1986) is that these natural constrains, which underpin "the natural order", are ontologically independent of human inquiry, perception and action. They do not vary with theoretical commitments, outlooks, interests or values of investigators or other actors. Hence, the question regarding the "back-inference" from laboratory phenomena to the world outside laboratories, and the relation of measurements carried over to the factual features of the world outside laboratories, is important for physics. In the following, I will first consider the "back-inference" of laboratory phenomena, and, secondly, the "back-inference" of physical reality revealed by measurement instruments.

4.3 Physical Knowledge Describes Potentiality

Considered from the material point of view, the "back-inference" of laboratory phenomena to the world outside of laboratories varies substantially: Part of the phenomena studied are completely non-natural, in the sense that they do not occur spontaneously nor without human intervention, for example Hall's effect, W-bosons, pure chemicals, and Andrew Crosse's "electrical life". But there also exist "more natural" phenomena, which are somehow "tamed" and reduced from the world outside of laboratories; for example, the mimetic experiments of the 18th century (e.g., Aitkens's miniature cloud-building (Galison and Assmus 1989), Van Marum's experiments with artificial clouds or Cavendish's model of electric fish (Hackmann 1989), Theodoric's study of rainbow geometry in water-filled flasks and so on). Somewhere between are the phenomena produced by apparatus/world complexes (e.g. subatomic apparatuses of the 20th century), the properties of which are neither properties of the apparatus nor properties of the world elicited by the apparatus, but are rather properties of a complex unit (Bohr 1958; Harré 2003).[13]

Even if the origin of the phenomena under study is more or less artificial, in practice it is assumed that "Nature" can have some decisive role in the outcome of the experiment and, thus, the underlining causal relationships are expected to be natural. Nevertheless, in an experimental invention, certain states of affairs are intentionally brought about, which would not have arisen without the interference and, moreover, of which we could also have chosen to realise another state than that finally chosen (Bohr 1958; Janich 1978).[14] For example, by running the original Bohrian apparatus of modern physics, we can provoke either particle phenomena or wave phenomena to occur, depending on which hypothesis or model the apparatus is designed to support (Bohr 1958). A somehow similar example is the cloud chamber mentioned above, the use of which can allow us to select either the study of meteorological phenomena or of elementary particles. Thus, can the experimentation be characterised as fully causal, while intentional action is important as well?

At least, physics does not fulfil the requirements of the Humean regularity theory, in which a causal relation is a constant causal conjunction of two actually occurring, natural events of a particular type. What experimental laws of physics describe is potentiality,

[13] Moreover, the different computer and thought experiments break down the empirical concept of experimentation: In scientific practices we find not only various sorts of hybrids of material interventions, but also computer, theoretical and mathematical simulations that are called "experiments". These "experiments", however, cannot be discussed here; for a detailed analysis, see Keller (2003) and Morgan (2003).

[14] Peter Janich and Niels Bohr discuss the same question in different traditions.

potential causality (Woodward 2003) or potential statistical regularity. We cannot expect those regularities to occur spontaneously or that they have been waiting there to be discovered, without human intentional action. Plainly, physics as such (only) reveals the ways by which we may interact with our physical environment. Hence, it would be better to interpret the causal claims of physics as claims about the outcomes of hypothetical experiments (Woodward 2003). Nevertheless, our conceptions of potential natural constrains give rise to those physical laws, which are thought to describe more general regularities. In logical empiricist accounts, the physical laws are seen as universal and true generalizations, but if considering from the constructivist viewpoint, the generalizing in such breadth is an unnecessary requirement (Giere 1988, 1999; chap. 5).

Consider, for example, the laws of free-fall, reflection and refraction, Coulomb's, Ohm's and Ampére's laws, Snell's Law, or the Zeroth law of thermodynamics: we cannot prepare a system which offends these laws, such that objects in a vacuum will not fall at the same speed, the angles of incidence and reflection of light rays will not be equal, the resistance in a metallic conductor in an electric circuit (defined as the power generated per unit of current squared flowing through it) will not be constant in a constant temperature, two thermodynamic systems, which are separately in thermal equilibrium with a third, would not be in thermal equilibrium also with each other, etc. They are not universal but describe only a vast variety of real-world systems. These "regularities" are created to the extent that they "appear" as such only within the ideal contexts. We can never test how these laws fit to the real-world systems. Instead, one can test the empirical representations, models of lower level made in their guidance. They can be "tested" only indirectly, by technological action, through materialisation of hypothesis of concrete experiments derived from the models constructed in their guidance; to get down an actual empirical claim we must designate a particular situation with a real set of values in a particular technological system (i.e. a material model). Only the similarity between certain features of a conceptual model and the certain observable features of a material model, and sometimes also the similarity between certain features of a material model and certain features of phenomenon occurring outside the laboratories, can be fitted through experimentation. Nevertheless, they are "natural laws" in physical reality. The instrumentariums and associated know-how and the technological knowledge, on which they are based, define the degree to which the empirical adequacy can be extended.

4.4 Truth Values of Physical Quantities

Elimination of the artificial data, for example by cutting out the "noise" or "background", is basic to transforming the experimental data into results. Selection criteria, usually referred to as "cuts", are applied to both the data themselves and the analysis procedures. Scientists refer to this refined data as genuine data (Franklin 1986), which includes the most accurate possible values of the measured quantities. But, how do these quantities, the basis of measuring, themselves relate to the world?

Instruments are never passive, because they are physical embodiments of design that have a teleological character, similar to all technology (see Ihde 1979; Mitcham 1994; Rothbart 2003) but laden with scientific, theoretical meanings. For example, the teleological character of the ohmmeter is to "measure resistance", which means reducing and modifying the complex system to one, by a theoretically defined dimension called "resistance of the object". Some instruments exceed the limits of our senses more than others. Hence, we need to at least "draw a distinction between what is observable, which is rather strict, and what is [merely] detectable, which is somewhat looser" (Fine 1986). For example, theories that underline the function of the "visual instruments" (such as a light microscope and a refracting telescope), differ less from the rules of our sense impressions than the theories of many instruments of electronics. A physicist is not the only one who appeals to theories underlying instrumentation. When they make use of physical instruments, the chemist and physiologist implicitly admit the accuracy of the theories justifying the use of these instruments as well as of the theories giving meaning to the abstract ideas of temperature, pressure, quantity of heat, intensity of current, and polarized light, by means of which the concrete indications of these instruments are translated (cf. Duhem 1914). Nevertheless, the physicist is the one who develops an understanding of both phenomena under study and the function of the instrument. In the other words, physicists develop the theory-laden nature of measurements. Measurement devices are theory-laden precisely in the sense that they are assumed to detect states of an experimental system by a regular causal relationship occurring potentially between the states of the "world" and the state of the instrument.[15] But, what does the "actual feature" of the "world", the "truth value" of measurement, mean in physical reality?

Scientific design is creation in a strong sense (Kroes 2003): by developing the method to measure a certain quantity, are developed the characteristics of the theory underlining the measuring. This kind of development of quantities can be described by the idea of "experimental regress" or "testers' regress" (Collins 1985; MacKenzie 1989). Thus, by deciding the criteria for the accepted method with which to measure, is decided the characteristics of the theory underlining the measuring process. Nevertheless, that is not necessary to say, that the foundation stone of measurement in physics is nothing more than the product of social construction (as, e.g., Harry M. Collins (1985) seems to think), but to clear the idea of "truth values" in physics. For example, in the case of quantifying in physics, the question of truth only makes sense if there is an objectively determinate value of the quantity in each physical system, but determining the truth values is bound to practical success (Chang 2004), i.e., successful operationalisation procedures. We can—and physicists often do—assume that in each material setting there is a real value for dimension with regard to the quantity in question. But it is impossible—and perhaps not even necessary—to prove the existence of such "real values" in the physical realm without reference to methods to measure it (cf. Chang 2004). To state "how abstract ideas relate to the world" by asking "what makes certain measurements true?", is the impossible attempt to step outside our skins—the immediate experiences, traditions, linguistic and other, within which we act, think and self-criticise—and compare ourselves with something absolute.[16] To understand the signal produced by an instrument, one needs to place it first and foremost in the field of constructed possibilities, that is, in some type of interaction with the world where a human is both instrument-maker and -user (cf. Baird 2004). The following chapter examines more closely the justification for *technoscientific* knowledge as an iterative "hunt for the real value" (Chang 2004), which we assume exists but which we do not know.

[15] Hence, the question of back inference of instruments is, whether there is an actual, constant relation between the change of certain feature(s) of the "world" and the observed change in the instrument (Harré 2003).

[16] This, nevertheless, does not necessarily mean reducing meanings of concepts to the independent instruments and circumstances in which the measurement is taken, as is suggested by operationalism. Neither does it necessarily imply that all knowledge, even the most esoteric theoretical concepts from the most uncommon fields of research, has meaning only to the extent that it provides a means to some end, as suggested in instrumental theory (e.g. Dewey 1916).

4.5 Scientific Design as Technological Iteration

Successful experimentation is guided by neither pure physical theory[17] alone, nor does it (necessarily) presuppose theoretical commitments. Rather, successful experimentation requires special knowledge and training in special experimental techniques, of which the story of the TEA-laser is a good example. Researchers could not transfer the expertise needed to build a TEA-laser through plain text from Canada to Britain; instead, they needed some concrete experience. In this special case, the successful transfer of "tacit knowledge" necessitated, firstly, a personal contact with an accomplished practitioner, and, secondly, the expertise was invisible so that scientists did not know whether they had the relevant expertise to build a laser until they tried it (e.g., Collins 1985). That was also seen in the historical way to guarantee the success of the replication of an experiment by sending material models, such as "Faraday's motors" Faraday sent, the electric coils William Thomson sent as part of his measurement of ohm and the gratings he ruled and sent. As Baird (2004) points out, Faraday made and shipped to his colleagues not conceptual, but 'pocket editions' of his new invention. In these material products included tacit know-how encapsulated his considerable operative skills, and thus anyone could replicate the experiment, even if he or she would not have the requisite skills. Material success in producing and controlling laboratory phenomena is somehow independent of the theoretical interpretations (Franklin 1986; Hacking 1983), and this has frequently made experimental success stable in the face of theory change.

Perhaps most obviously independent of theoretical interpretations was the development of the foundation for classical physics: Much of the early developments in optics between the 17th and 19th centuries simply depended on noticing some surprising phenomena and employing practical methods used by different practitioners to produce (mime) and control the same phenomena in the laboratory. The foundations of both thermometry and barometry were created without agreement on a theoretical definition for pressure, temperature or heat, because no established theory was capable of guiding the design until the 19th century (see Chang 2004; Middleton 1964). In this development, the everyday contact with material bodies, which unites sensation with conception (hot and cold, change in length, time, strength and brightness of objects), served as the basis of required quantities. The C.T.R. Wilson's cloud chamber is also a good example of the (material) stability of a designer's success "under theory change", because it makes a material intersection and later transformation between meteorology and matter theory, between two traditions: mimetic and analytical (for details see Galison and Assmus 1989). The original meteorological phenomena mimicking machine, was received by his Cavendish colleagues as a means to study quite different phenomena. Most notably the cloud chamber was employed by J.J. Thomson, who employed (and developed) it to measure a value for the charge of "the electron" and to support his growing conviction that the electron was a fundamental particle.

Nevertheless, to "know how to make that" is not to "know that", and vice versa. Scientists (or pupils following educational instructions) may achieve remarkable instrumental control over laboratory phenomena without correctly understanding the functioning of the phenomena under study and instruments employed; or, vice versa, one may gain excellent conceptual control without being able to exploit that control technologically. A good example

[17] Instead of abstract theories, skilful experimentation employs (and also develops) a special kind of technological knowledge (Mitcham 1994), "experimental knowledge" (described above, in Sects. 2.3 and 4.1). Naturally, technological knowledge (also that used in experimentation) includes more; for example it is also knowledge about the economical, political, ethical and social constraints of designing which constitutes the above mentioned socio-technological understanding.

is Thomas Davenport, who succeeded in making an electromagnetic motor after seeing a demonstration of Joseph Henry's electromagnet, even though he had only a little schooling and no training in electromagnetism (see Baird 2003). Experimentation becomes scientific, as distinguished from random constructive and manipulative action in the material world, only within a scientific theoretical framework. This scientific theoretical framework guides the process from the formation of the model to be tested and developed, lying down of research questions and the design and construction of experimental settings (and learning to use it) to purification and interpretation of the results. The objective of design is that the theoretical framework itself becomes revised in the iterative design processes.

Hence, in the progress of science, "know-how" and "know-that" develop in mutual interaction; the design process combines the stage of "knowing" and "doing" into a continuum, or at least forms a stepwise sequence between the abstract level of theory and the material level of action.[18] This medium is written in design plans, which guide both the materialisation of ideas and symbolic interpretation of them. For example, in the beginning of the design process of an instrument, physicists had a theoretical assumption or "practical theory" forming the basis of a measurement technique, which expresses the quantity to be measured (e.g. temperature or air pressure) as a function of another directly observable quantity (e.g. a height of a liquid column or the colour of a test object). The design process aims to sharpen the measuring techniques by increasing simultaneously both the understanding of the material relationship between these quantities, and the material control of the quantities. The thermoscope and baroscopes provided a more accurate basis upon which to compare temperatures and pressures of objects or systems as senses, while thermometers and barometers were more accurate in comparison than thermoscopes and barometers, etc. (see Chang 2004; Middleton 1964). The aim of the scientific design of a measurement instrument is to reach the greatest degree of technically feasible accuracy, and then extend the technical limits for future progress. Thus, the invention of the thermometer and barometer was guided by prevailing "know-how", which itself was improved in the process.

Progress means the crossing of limits of particular material settings, reproduction of the materialisation of the ideas in different material settings. Several methods were also used to measure the exemplary "temperature", since any object that has a thermometric property, i.e. a physical property that changes in a constant way as the object gets colder or hotter, can in principle be used as the basis for a scale for temperature. Nevertheless, by developing a variety of methods to measure "temperature" not just one, but rather a series of definitions were invented, each defined by different thermometers, but referred to and by the same term, "temperature". Different temperature scales tied the concept to particular phenomena, in a particular system. To compare the temperature measured by different thermometers, the practitioners needed to standardise plausible procedures for measurements and methods to compare different measurements. The definition of general, scientific procedures for temperature measurement in the 17th and 18th centuries, would have proposed putting down a set of operational norms, but as mentioned earlier, no established theory on which to base them existed at that time. Naturally, even that was not enough for scientists studying thermometry. Thermodynamic understanding had to extend beyond the differing material meanings, which can, following Hasok Chang (2004), be called "hunting for real value"

[18] Naturally, the development of instrumentation also provides research constructing "know-that", which is not in any way linked to this functioning and for which the instrumentation function is a black-box. For example, consider different kinds of microscopes in past and present use by biologists, or any instrument or apparatus used in physical research after establishing the theory underlying its function.

of temperature. How was it that the thermometers where justified while there was no precise standard of quantity temperature as the one reached by thermometer(s) itself?

This "crucial" design of theory and experimentation can be explained by the iterative development of independent, yet interactive, stages of "know-how" and "know-that" knowledge. Physicists adopt at every moment the existing systems of "know-how" and "know-that" knowledge and existing material abilities to control experimental systems (without any firm assurance of the correctness and accurateness) and, moreover, they aim to sharpen and correct them both (cf. Chang 2004). This self-correction of basic concepts, and laws of new theories, along with the ability to measure the related quantities, develops in simultaneous interaction with the world merged to the scientific design process. In this way, technology modifies and affects physical knowledge, and through providing limits and forms for physical reality accessible to us, it also necessarily affects our conception of reality.

5 New Views on Science Education: Technoscience Education

In physics education, the experimental work and associated skills of handling the experimental apparatus and measuring instruments has long been considered to be an integral part of learning physics (Hodson 1986). In addition to acquiring certain skills, these activities are important because they support conceptualisation, learning of content and they teach about the empirical foundation of science (see e.g. Koponen and Mäntylä 2006 and the references there). This could also bring forward the important cognitive role of technology in physics. Nevertheless, science and technology education, both as distinct and integrated subjects (Layton 1993) still rely on and teach about a traditional conception of science and technology as fundamentally different and distinct enterprises. Many new ideas discussed here can be implemented in the already existing framework: the three basic notions of the nature of *technoscience*, introduced in this study, guide the organisation of the science- and technology-based elements of education in a new and fruitfully unifying way. Additionally, *technoscience* adds to our understanding of what "empirical nature" means in the case of physics. Hence, any notion of "nature of science" (NOS) should properly take into account technology and technological action.

As an educational approach and content, *technoscience* embodies a moderate constructivist view to science (as described in Sect. 2), but rejects the radical contructivist views as well as the radical constructivist epistemologies. In science education, there has been a period of emphasis on the discovery aspect of knowledge production in learning, and these views have been the hallmark feature in many oversimplified constructivist views on learning (see Hodson 1986; Mayer 2004; Millar and Driver 1987; Nola 1998). According to these views, teachers should not tell students anything directly but should, instead, allow them to construct all knowledge by themselves; successful learning is thought to be achieved through exploration and experimentation and also knowledge production in students' minds is believed to be fostered purely on this basis. In the *technoscientific* view, experimentation and experiments also play a central or even crucial role, but it gives experiments a very different role than they have in discovery learning or in learning by inquiry. In addition, emphasis on experiments does not mean adopting empiricist stance. Similarly, noting the advantages of a constructivist view to learning—recognising the simple and always understood fact that existing knowledge is needed to construct new knowledge and that, in addition to skills of abstract thinking, also skills of building, constructing and manipulating things are needed to build new knowledge—does not necessitate adopting the thesis of discovery learning. It is now a well demonstrated and discussed fact that these naïve conceptions of empiricism, and of constructivism and learning models based on them, are difficult if not impossible to support in the face of the historical record of science, as well as research-based evidence about learning results (Kirschner et al. 2006; Mayer 2004). However, the rejection of naïve conceptions of empiricism and contructivism should not lead to another class of naïveté, which views any empiricist conception as being unsuitable to serve as the basis for educational solutions, or which fails to see the difference between constructive knowledge building and simple forms of constructivism. In this latter sense of appreciating constructive knowledge building and the sophisticated relationship between experiments and technology, *technoscience* is founded on constructivist views as an educational approach. At the same time, however, it has to be understood as suggesting guided learning processes highlighting the constructivist role of technology in science.

Physics, as an empirical science, is inexorably linked to technological productivity and capability; what this means is that physics as an empirical science is essentially defined by technology.[19] *Technoscience* supports the conception that physical reality is revealed through, as well as modified by, technological action: it differs from the equally deficient views that an experimental method is necessary for the verification of theories, and instead deepens understanding of the generative nature of experimentation in theory formation. Contrary to traditional views, *technoscience* enforces the view that active manipulation and intervention through experimental activity is an act of constructing our conceptions of what exists in the world and how it does so. Hence, *technoscience* embodies and improves the frequently mentioned general notions of NOS, such as “science is creative” and “scientific knowledge is theory-laden and tentative” (for more examples see Lederman et al. 2002; Sandoval 2005) in the concrete practices of science. Naturally, *technoscientific* view does not encompass all the variety of meanings those general notions may encompass. The advantage of *technoscience* is that it approaches education from the perspective of the working scientist, and avoids fixing upon any specific philosophical orthodoxy or fashionable theme (be it empiricism, realism or a model-based view). In addition, it sheds light on the fact that the NOS notion of “the empirical nature” of physics—which is certainly of much interest and often a slogan in textbooks—cannot be understood correctly without paying close attention to the role of technology. A process, in which science makes progress where also technological advantage is central, employs “a variety of methodologies” (also one of the NOS themes); *technoscience* actually shows how these methodologies are constructed. This is true, insofar as *technoscience* reveals that the scientists discover through creating material as well as conceptual artefacts, models of different levels, by developing those in mutual interaction in the creative design processes (as described in Sect. 4). The design takes place in a theoretical framework, which itself becomes revised in the design process, through developing and employing technological knowledge (Sects. 2.3, 4.1 and 4.5). This requires total immersion in the previous theories and scientific worlds and in the tacit and explicit knowledge and skills of the experimental work (“theory-laddeness of science”). Nevertheless, since scientific knowledge can be developed only within particular material settings, that knowledge can never acquire the status of an absolutely proven universal truth (Sects. 4.4 and 4.5). Finally, the justification of iterative design processes lies in practical functionality of materialised ideas, which itself is socially defined. In such a way, the *technoscientific* view to NOS is essentially bound to the practices of science. Since *technoscience* emphasizes the constructive nature of knowledge construction, which does not commit to either side of the

[19] The perspective on the relation between science and technology is often omitted as belonging to the definition of NOS, but the presented views have not taken into account the epistemological and cognitive role of scientific technology in scientific progress.

debate on empiricism vs. realism, it can be employed to support understanding about NOS regardless of the metaphysical commitments of students or teachers.

In practice, highlighting the technological nature of physical reality can be supported by moderately implementing the ideas of knowledge construction through the scientific design of experiments in education as methodological means and contents. In experimental design, also failure is a familiar thing, naturally understood as a lack of control over nature, and it is always amenable through the sharpening of both understanding and control. Hence, *technoscience* can help students to see science as an active, creative process. In such a manner, *technoscience* also supports students' own construction of knowledge and provides an active and essential role in this process for tools, instruments and apparatuses. Since *technoscience* emphasises the human being's active, creative role in the formation of concepts, laws, and theories, it also supports in a natural way the teaching solutions, which put weight on personal conceptualisation for learning. In regard to the active role of learners, *technoscience* thus promotes the connection between "doing" and "learning", because it stresses the intertwined character of experimental explorations and theorising, and acknowledges the central role of material devices. To design something is not to follow recipes, but rather to think and act creatively and critically (Layton 1993; Mitcham 1994; Rothbart 2007; Vincenti 1990) in order to realise cognitive goals, which can be achieved only through, and merged with, technological devices. Consequently, by emphasising the primary role of experiments in building up conceptual structures, the *technoscience* approach encompasses coherent conceptualisation and conceptual understanding—the traditionally valued goal of all physics education. *Technoscience* links the abstract concepts to each other and to the physical world in the cognitive-material medium of design (as described closer in Sects. 4.1 and 4.5), which provides students with a concrete view to modelling as a means for producing scientific knowledge (see Sect. 2). In this manner, it eases the understanding and application of ideal physical laws (Sect. 4.4). Moreover, *technoscience* guides understanding, what is the area of application of this knowledge and, shows how we have succeeded in "knowing" that.

Over the last 30+ years, the NOS-views have been steadily improved by reflective exercises and, especially, by including historical aspects of science in teaching (see Lederman et al. 1998).[20] *Technoscientific* educational tasks can naturally combine both historical narratives and hands-on working, the design of which is moderately guided by views of different design-, problem- and context-based approaches—moderately for the misinterpretations explained above. The use of narratives reconstructed from the *technoscientific* viewpoint, and reflecting the practices of the classroom to the practices presented in these narratives, can guide understanding of both scientific contents and practices.[21]

[20] It is not appropriate to teach NOS only explicitly (as exercises or stories distinct from the current conceptual contexts under study) but it cannot either be taught only implicitly (by imitating scientists work in school laboratories). In addition, several arguments seeking the place of NOS in curricula have emphasized an understanding about the social nature of the scientific process. In reality, the relationship between practical and formal NOS views and teaching and learning is found to be very complex; and thus the empirical evidence argues for the middle ground of these approaches (Lederman et al. 2002; Sandoval 2005).

[21] The constructivism in education implies that, primarily, students must be cognitively active during learning, not that they should be overly behaviourally active. The cognitive action, in this case, should not be disturbed by overloading the working memory by excessive behavioural activity (Kirschner et al. 2006; Sweller et al. 1998). The needed flexibility in guidance can be reached, for example, by dividing the problem into smaller parts and implementing the partial-problems in an interrupted storyline; the wider *technoscientific* design problem is thus solved by designing (for example, a way to quantify and measure at the beginning of the process of a yet unknown quantity) while the story goes on.

Thus, designing *technoscientific* tasks involves not only the usual motivational factors (Layton 1993), but becomes guided by a human being's aspiration to understand the environment scientifically.

In sum, *technoscience* improves the authenticity and coherence between the NOS-based and conceptual and procedural elements of contemporary science education by learning from the coherence between the respective—theoretical, methodological and epistemological—elements in scientific practices, and in this a manner it improves the learning process. Ultimately, the *technoscientific* view leads us to see technology not only as a vehicle towards more reliable and accurate knowledge, but also as a part of physical objects and value as an object of scientific research itself. As an essential provider of physical reality that is accessible to us, technology is not a neutral intermediator of physical knowledge but rather an active modifier of it, which, finally, transforms our conception of reality.

6 Conclusion

The dominant theories of science education today fail to assimilate recent studies on the interface between science and technology. In the classroom, this failure perpetuates distorted and over-simplified conceptions of science. The needed complementary view, that is, the unifying view of physics and technology, is suggested as being the *technoscientific* view, introduced here. *Technoscience* considers physics and technology to be so intimately mutually interdependent that technology has a distinctively cognitive role to play in physical theory formation and, moreover, an epistemological and cognitive role, even to the extent that it affects our ontological positions.

Technoscience serves a more authentic and constructive image of the role of technology in physical progress: it helps to conceive technology in its correct historical role and provides teaching to the practising physicists' familiar constructive role of technology. Since, *technoscience* combines traditionally distinct science- and technology-based elements of education, using it as a basis of education increases coherence and unity of physics as a subject. Furthermore, since *technoscience* promotes the connection between "knowing" and "doing", this coherence becomes extended throughout the personal learning processes. Hence, the *technoscientific* viewpoint makes it possible to retain those aspects of experimenting and design in education, which make them purposeful for learning, by providing a starting point for students' own construction of knowledge during the learning process.

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