SCIENCE, TECHNOLOGY AND THE SCIENCE–TECHNOLOGY RELATIONSHIP

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1 INTRODUCTION

This chapter discusses the principal philosophical questions concerning the relationship between science and technology. As for science, the discussion is meant to cover a variety of disciplines, even if the examples show some emphasis on the natural sciences.[1] As for technology, in the present chapter this notion will be used in a broad sense. That is to say, technology is taken to embrace the technological sciences, while the technological sciences include several disciplines in addition to the engineering sciences, such as information science, medical science, and agricultural science. Making such a direct link between technology, more broadly, and the technological sciences makes sense in view of the fact that these sciences aim to contribute towards realizing contemporary or future technologies. Accordingly, the chapter includes discussions and illustrations of a broad range of technological activities, such as research, design, production, use and maintenance. This also fits the comprehensive approach to technology and the engineering sciences that is taken in this Handbook.

The prime subject of this chapter is the relationship between science and technology. That science and technology have been, still are, and can be expected to remain, 'related' hardly needs to be argued. Rather, the important questions concern, first, the empirical features of this relationship (including its historical development) and, second, its theoretical conceptualization in relation to our philosophical understanding of both science and technology. As will be demonstrated in this and the other chapters in this part of the Handbook, these two questions may receive quite different answers.

The layout of the chapter is as follows. Section 2 discusses some important methodological issues that naturally present themselves to a reflexive philosophical approach. Since any account of the science-technology relationship presupposes some characterization of both science and technology, the question is how to acquire a plausible characterization. As to the relationship between science and technology, we face the related methodological question of how to study this relationship. The sections that follow then review several important views of science,

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[1] For a review of the role of the social sciences in technology and engineering, see Sørensen's chapter in this Volume, Part I.

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technology and their relationship: the idea of technology as applied science (Section 3); the conception of the technological finalization of science (Section 4); the claim that experimentation constitutes the central link between science and technology (Section 5); and the account of science as technology (Section 6). Section 7 sums up the main conclusions about the science-technology relationship and, in particular, about the uses of science in technology. Overall, I follow the common philosophical practice of presenting both an exposition and a critical assessment of the views discussed. Where appropriate, references to other chapters of this Handbook, both in this and in the other parts, are provided.

2 PRELIMINARY METHODOLOGICAL ISSUES

A reflexive philosophical study of the relationship between science and technology needs to confront some preliminary methodological issues. Since making claims about the nature of this relationship presupposes some characterization of science and technology themselves, there is the question of how to acquire a plausible specification of these notions. Next, there is the closely related question of how to investigate the science-technology relationship itself and how to obtain a fitting account of it.

The question of how to characterize science and technology is often addressed through a specification of their respective aims. Many authors claim that the aim of science is epistemic, and in particular, the acquisition of knowledge. The aim of technology, in contrast, is said to be the construction of things or processes with some socially useful function. Many other authors, however, claim that such a conceptual-theoretical specification of science and technology does not do justice to the richness and variety of actual scientific and technological practices. By way of alternative they advocate a nominalistic-empirical approach: go and see, and define science (respectively technology) as the practical activity that is called science (respectively technology). These two points of departure — either a conceptual-theoretical definition or a nominalistic-empirical account of science and technology — differ greatly. Both lead to several further questions.

Consider first the view of science as the search for knowledge. Since there is also nonscientific knowledge, some authors add that science is the activity that systematically strives for theoretical and explanatory knowledge. However, a strict application of this definition would exclude many activities that are usually, and rightly, seen as part of science. Quite a few scientists aim at observational or experimental knowledge and scientific knowledge can also be non-explanatory, for instance in the case of taxonomical knowledge. A possible solution might be to distinguish between primary and subsidiary aims. Accordingly, the search for theoretical, explanatory knowledge would be the primary aim of science, while other types of knowledge are always subsidiary to this aim. This solution is rather questionable, however. It is, for instance, difficult to reconcile with the many studies that have convincingly shown that experimental practice has an extensive and worthwhile life of its own.[2]

Furthermore, defining science as the search for theoretical, explanatory knowledge presupposes a specific philosophical interpretation of science, which will not be generally acceptable. Thus, Bas van Fraassen [1980] sees explanation as merely a pragmatic aspect of science and he puts forward the empirical adequacy of theories, instead of their truth, as the aim of science. Patrick Heelan [1983] also emphasizes the primacy of perception, although his notion of perception differs significantly from van Fraassen's account. Clearly, for these philosophers and their followers a plausible characterization of science, and a fortiori of the contrast between science and technology, cannot be based on the explanatory nature of theoretical science.

What about the definition of the aim of technology as the construction of things or processes having some socially useful function? Although this definition seems to be intuitively plausible, two qualifications are in order. First, many authors claim that it is too narrow because technology is not limited to the making of useful material things or processes. Technology, as the etymology of this term suggests, also involves the generation and utilization of knowledge ([Layton, 1974]; see also the chapters on artifact epistemology in Part II of this Handbook). More specifically, it is design knowledge that is claimed to have a prominent place in technology. Moreover, in the engineering or technological sciences, this design knowledge is often of a quite general nature [Kroes, this volume, Part III].

Second, this definition of technology (with or without the addition of design knowledge) is not of much help in clarifying the science-technology relationship. After all, designing and constructing material things or processes, including the generation and utilization of design knowledge, is common business in the practices of observational and experimental science.[3] Both the overall observational or experimental setup and their component devices, apparatus or instruments often require an extensive process of design and construction (see, e.g., [Rothbart, 2007]). Such observational and experimental practices constitute a major part of scientific disciplines. Hence, in contrast to what Layton [1974], Kroes [1992] and many others claim, design (knowledge) and construction do not demarcate technology and engineering from science.

What to conclude from this discussion of the conceptual-theoretical approach? The only tenable intuitive distinction seems to be the relation to social usefulness. In contrast to science, technology would be oriented towards potential usefulness for society at large. Even this suggestion needs to be qualified, however. First, should this social usefulness be explicit and immediately visible, right at the start of a technological project? In this case, some of the research carried out in industrial laboratories may not qualify as technological. For instance, the research done

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[2] See, e.g., [Hacking, 1983; Gooding, 1990; Galison, 1997; Lange, 1999; Radder, 2003; Baird, 2004].

[3] Even computational science has a material side and hence it involves some design of material things or processes. See the analysis of the simulation laboratory in [Petersen, 2006, Chap. 2].

between 1947 and 1972 at the Philips electronic laboratories did not always aim at immediate technological applications [De Vries, 2005]. But if social usefulness is permitted to emerge in the course of a project, then quite a few projects in prima facie scientific research will also count as technological. After all, basic research is often supported by funding agencies because of its contribution to the 'knowledge base' of a society, and hence this research can be seen as practically useful in the long run (cf. [Tiles and Oberdiek, 1995, Chap. 4]). For this purpose, present-day applications for basic research projects have to be routinely justified also in terms of their possible technological and societal payoff.

Let us now have a closer look at the nominalistic-empirical strategy. This involves the empirical investigation of whichever activities that present themselves as scientific or technological. As will be clear from the preceding comments on the conceptual-theoretical approach, this nominalistic-empirical strategy certainly has its place. In particular, it constitutes a healthy antidote against those philosophers who simply proclaim a specific aim for science or technology, without any further evidence or reflection. Yet, although this strategy may initially seem straightforward, on closer inspection it appears to have its problems as well.

First, any empirical identification of either science or technology requires some pre-understanding. Suppose we visit a site called 'Institute for Biomedical Science'. We may, then, safely conclude that this is a site of scientific activity. But many different activities take place in this institute: the toilets are cleaned, the board of directors holds meetings, the catering service provides lunches and the PhDs write articles. When we focus on the writing of articles in studying science, we apparently apply a certain pre-understanding of what counts as (the core activities of) science. Thus, [Latour and Woolgar, 1979] characterize laboratory science through its production of 'inscriptions' (and not, to mention another option, through its catering procedures). More precisely, they focus on a specific subset of the inscriptions produced in the laboratory and disregard other inscriptions, such as the receipts generated by the PhDs through having their lunch in the lab canteen. Hence, the nominalistic-empirical approach presupposes some conceptual-theoretical interpretation of what constitutes science and technology, and the question of whether we can make this pre-understanding more explicit, or even define it, is still with us.

A second problem of the nominalistic-empirical approach is that different languages and cultures use different names for activities that might be quite similar. Anglo-Saxons distinguish sciences and humanities, which in Germany are both called *Wissenschaft*. In earlier centuries, natural philosophy denoted what is now called physical science. And nowadays we speak of computer science and information technology as being roughly equivalent. In order to see whether or not such types of activities might be essentially, basically, or to a large extent similar, we again need a conceptual-theoretical clarification of those activities.

My conclusion from this preliminary discussion is that we need both the theoretical and the empirical approach. We have to start from some interpretive perspective on what we take to be basic aspects of science and technology. Next, we articulate and test this interpretation on the basis of the empirical study of the activities thus defined. And we try to determine its scope by examining its possible applicability to natural philosophy, humanities, information technology, and the like. Once we have established a plausible interpretation of science and technology, this interpretation will acquire some normative force. Activities that do not conform to the established characterization of science or technology should not be named scientific or technological. We stick to a particular interpretation as long as it enables us to cover (what we take to be) the interesting and important cases and dimensions of both science and technology. Thus, the theoretical and the empirical approach should not be separated. On the one hand, a plausible conceptual model should be backed up by empirical studies of the practice of science and technology. On the other, an empirical investigation presupposes an interpretive pre-understanding of both science and technology, and an appropriate empirical model of the science-technology relationship needs to be based on a plausible interpretive pre-understanding. In this chapter, the emphasis is on conceptual-theoretical accounts of the relationship between science and technology, but I will also pay attention to the empirical support of those accounts and refer to empirical studies of this relationship. David Channell's contribution [this volume, Part I] provides more detailed discussions of several important aspects of the empirical relationship between science and technology.

3 TECHNOLOGY AS APPLIED SCIENCE

A still current view of the relationship between science and technology is phrased by means of the formula 'technology is applied science'. A classic account of this view has been presented by Mario Bunge. He makes the following distinction between technology as applied science and pure science.

> The method and the theories of science can be applied either to increasing our knowledge of the external and the internal reality or to enhancing our welfare and power. If the goal is purely cognitive, pure science is obtained; if primarily practical, applied science. Thus, whereas cytology is a branch of pure science, cancer research is one of applied research. [Bunge, 1966, p. 329]

Thus, it is the distinct aims which differentiate (pure) science from technology. In Bunge's view, these aims pertain to the outlook and motivation of the scientific and technological researchers. Bunge develops this view as follows. Scientists strive for empirically testable and true theoretical laws, which accurately describe (external or internal) reality and which enable us to predict the course of events. The technologist, in contrast, uses scientific laws as the foundation of rules which prescribe effective interventions in, and control of, this reality for the purpose of solving practical problems and realizing social objectives. Taken together, science and technology (the latter in the sense of applied science) should be distinguished from those practical techniques and actions that are not based on scientific theories or methods. Thus, in this view, Roman engineering and medieval agriculture are practical arts and crafts rather than technologies. Since experimentation is a basic method for testing scientific theories, Bunge distinguishes experimental action from both technological and purely practical action.

Bunge [1966, p. 330] claims that the different aims of science and technology are inferred from alleged differences in outlook and motivation of their practitioners. If this were meant in a literal sense, he should have provided us with the results of empirical investigations, such as surveys, interviews, or other evidence about the attitudes or self-images of scientists and technologists. Apparently, this is not Bunge's intention. Instead, his discussion suggests that he thinks that these outlooks and motivations can in some way be 'derived' or 'reconstructed' on the basis of the activities of scientists and technologists. Hence, the discussion in this section focuses on these (alleged) differences in scientific and technological activities.

A further characteristic of this account of the science-technology relationship is its hierarchical nature. In particular, Bunge postulates an epistemological hierarchy between science and technology. If true, scientific laws can provide a justification of technological rules. The converse is not possible, however: a working technological rule, which is merely practically effective, can never justify a scientific law. By way of example, he discusses the technology of making an optical instrument, such as the telescope. In designing and constructing such a device we do not exclusively employ wave optics, the most truthful theory of light in this context, but make ample use of the false theory of geometrical optics, which conceives of light as propagating along straight lines. Moreover, usually such construction work requires specific craft skills (such as the grinding of the lenses or mirrors) which do not employ scientific theories but are based on effective practical know-how and procedures. Bunge concludes that a practically working artifact, such as the telescope, cannot justify the scientific laws employed in its construction.

In addition to the epistemological primacy of science over technology, Bunge's view entails a temporal ordering. If technology is the result of applying science, it follows that temporally prior scientific research constitutes the driving force of technological development and innovation. This idea of 'science finds — industry applies' is often called the linear model of the science-technology relationship.

More or less similar hierarchical views of the science-technology relationship can also be found outside of philosophy, for instance among scientists, policy-makers, and the public at large. Sometimes such views include an even stronger hierarchical evaluation in that science is seen as an exciting, creative quest for truth, while technology would merely involve the routine application and exploitation of the fruits of this quest.

In the remainder of this section, I discuss and evaluate this view of technology as applied science.[4] First, several scholars have criticized Bunge's approach on

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[4] In doing so, the focus will be on the 'substantive' theories of scientists and engineers, that is, theories about the technological objects themselves, thus leaving aside the 'operative' theories of social scientists and technologists, that is, the social theories about technological action and

historical grounds. They claim that historical studies show that many important technological inventions and innovations came about independently from scientific research and scientific theorizing. Well-known illustrations include steam engines, water power devices, mechanical clocks, metallurgical techniques and the like (e.g., [Laudan, 1984]; see also Channell's chapter in this Volume, Part I).

Although these criticisms seem basically correct, they do depend on the precise interpretation of Bunge's version of the linear model of the science-technology relationship.[5] A flexible interpretation of Bunge's model would permit the following replies. First, many of the historical counterexamples date back long ago, often to the eighteenth century and before. Hence, they need not be taken as a refutation of the account of technology as applied science, but might be seen as limiting the scope of this account. Put differently, Bunge's account might be construed as a *definition* of technology and as such it would be immune to empirical counterexamples. If a certain case does not fit the account of technology as applied science, then it is, by definition, not a technology. The remaining issue, then, pertains to the usefulness and relevance of Bunge's definition. In view of the great significance of modern, science-based technology, the usefulness and relevance of his definition seems obvious enough. Second, one might note that, in Bunge's view, technology may also result from applying the *method* of science (see the above quotation) and that one could make a case for the claim that (some of) the counterexamples did apply scientific methods, even if they were not based on available scientific theories.

However this may be, I will not pursue this debate any further here but instead develop a different assessment of Bunge's technology-is-applied-science account. For this purpose, it is important to realize that this account implies two distinct claims. The first is that there is a clear 'kinship' between science and technology, in the sense that technology is based on scientific theories and methods. The historical criticisms are aimed at this claim. They seem to accept Bunge's characterization of science as a quest for true knowledge of laws and theories (e.g., [Layton, 1974]), but they object that technology has often developed independently from these laws and theories. That is to say, they claim that the differences between science and technology are larger than Bunge assumes. Secondly, however, Bunge advocates the claim that science and technology also display essential differences, in the sense that scientists aim at truth and technologists at practical effectiveness and usefulness. I will assess this second claim by analyzing, like Bunge, science-based technology and by showing that its contrast to science is much smaller than Bunge assumes.

Consider the claim that scientists aim for truth by constructing testable, fundamental theories and by accepting or rejecting these theories according to their match to the empirical data. This account suggests that separate, fundamental theories can be confronted more or less directly with the empirical data. In fact,

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organization (for the latter, see Sørensen's chapter in this Volume, Part I]).

[5] For extensive, critical discussions of the linear model, see the contributions to [Grandin *et al.*, 2004].

however, scientific practice is much more complex. Fundamental theories as such, for instance quantum mechanics or the theory of evolution, do not tell us much about empirical reality. To become empirically applicable they first have to be developed and specified with a view to particular domains of empirical phenomena.

The point can be illustrated by the case of nonrelativistic quantum mechanics. The basic structure of this theory was developed between 1925 and 1927. Since those days, this theory has been, and is being, 'tested' in many different domains, including atomic and nuclear physics, quantum chemistry, solid state physics, and so on. Within each of these domains we find a diversity of subfields, such as the study of electrical conductivity in crystals within solid state physics. Moreover, there are overlapping research areas, such as laser physics which combines insights from both atomic and molecular physics and from quantum electrodynamics.

Hence, we are confronted not with two types of activities (theoretical and experimental) but three: the construction of fundamental theories; their development and specification to enable actual empirical tests; and the design and performance of experiments to test the theories. The second type of activity requires the articulation of the fundamental theories, usually through extensive calculation and substantial model building.[6]

Two aspects of these processes of development and articulation are particularly relevant to the present comparison between science and technology. First, even within one subfield one often finds a large variety of different models and methods of calculation, each of them specific for and appropriate to particular types of experiment. Nancy Cartwright [1983, pp. 78-81] discusses the example of laser physics and documents the use of at least six different models of the natural broadening of spectral lines. She emphasizes that the scope of each of these models is often quite small, namely limited to a few types of experimental phenomena. Moreover, scientists do not see these different models as competing but rather as complementing each other since each serves a specific purpose.

Second, a major function of model building is to bridge the large distance between the relatively schematic and simple fundamental theories and the mostly complex experimental world [Morgan and Morrison, 1999]. Because of this distance, bridging cannot succeed on the basis of the fundamental theories alone. Hence, what we see in practice is the use of a diversity of methods and approaches that cannot be rigorously justified from a theoretical perspective. Frequent use is made of convenient rules of thumb, intuitively attractive models, mathematically feasible approximations, and computationally tractable computer simulations. Often the test also depends on other experiments, for instance when the value of parameters that cannot be calculated theoretically, is determined through tuning them to the results of other experiments.

Thus, the variety of experimental domains and the large distance between fundamental theories and experimental phenomena require the indispensable use of

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[6] See [Böhme *et al.*, 1983; Cartwright, 1983; 1999]. For the sake of argument I have, with Bunge, assumed the availability of a fundamental theory. In actual practice, calculation and model building may just as well precede the construction of such a theory.

'workable methods' in testing the theories. Scientific practice includes the regular application of a variety of convenient rules of thumb and intuitive models for solving different problems, the making of approximations based on mathematical or computational feasibility and the blackboxing of (part of) a system through tuning to experimentally determined parameters. The crucial point is that these are exactly the kinds of procedures that are typical of technology, *also according to Bunge*. Thus, on the basis of an analysis of their testing activities, there is no reason to assume a fundamental contrast in outlook and motivation between scientists and technologists.[7] A test of quantum mechanics by a laser physicist is not essentially different from the test of a design of a specific acoustic amplifier by an engineer [Cartwright, 1983, pp. 107-112].

Thus far, I have focused on Bunge's account of the relationship between science and technology as applied science. Apart from this, there is his claim that both science and technology should be clearly distinguished from skillful, practical action. This claim suggests that practical craft skills play no (or no significant) role in science and in science-based technology. However, if we — in contrast to Bunge — take full account of the practice of scientific and technological observation and experimentation, it is immediately clear that this suggestion makes no sense. After all, as every observer or experimentalist knows, skillful action is an essential aspect of observational and experimental science and technology (just think of the grinding of the lenses in the case of constructing a telescope).[8] The reason for the importance of skillful action is straightforward. In contrast to what generations of empiricists have claimed, the typical way of obtaining scientific experience is not through passive sensation but through active observation and experimentation. As we will see in more detail in Section 5, the stability and reproducibility that scientific observers and experimenters try to establish is almost never given by nature, but has to be realized through a difficult and laborious process of intervention and control. For this purpose, skillful practical action is indispensable (see, e.g., [Ravetz, 1973; Collins, 1985; Gooding, 1990; Radder, 1996]).

The discussion in this section does not claim to provide an exhaustive assessment of the view of technology as applied science.[9] Yet it should suffice to demonstrate that Bunge's hierarchical approach is questionable. A reconstruction of their cognitive activities does not support the attribution of essentially different aims to scientists and technologists. Consequently, this way of demarcating science from technology proves to be difficult, if not impossible, and the same applies to sub-

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[7] Another relevant argument, which I will not pursue here, is that scientists do not aim at truth simpliciter but at significant truths, where the criteria of significance may be both epistemological and social (see [Kitcher, 2001]).

[8] In a later publication, Bunge admits that 'even the scientific inventor is a bit of a tinkerer (*bricoleur*) and — like the scientist — he possesses some tacit knowledge, or know-how, that cannot be rendered fully explicit' [Bunge, 1985, p. 220]. In spite of this, he immediately adds that it is only explicit, science-based technology that is philosophically interesting and worth studying.

[9] For further discussions and assessments, see [Tiles and Oberdiek, 1995; Cuevas, 2005; Boon, 2006; Koningsveld, 2006]. See also Channell's chapter in this Volume, Part I.

stantiating the epistemological subordination of technology to science. To avoid misunderstanding, I should like to emphasize that the argument of this section is not that there are no differences at all between science and technology. But it does imply that, generally speaking, these differences will be a matter of degree and that they do not add up to an unambiguous contrast between science and technology in terms of singular and essentially different aims. In the concluding section of this chapter I will come back to this issue and address the question how science and technology may be distinguished and related on the basis of their similarities and dissimilarities.

4 TECHNOLOGY AS FINALIZED SCIENCE

During the 1970s a group of German scholars, also called the Starnberg group, published an impressive series of articles and books about the finalization of science (see [Schäfer, 1983], and further references therein). 'Finalized science' denotes a particular stage of scientific development that is, more or less consciously, oriented towards external social goals and interests. The authors themselves see their finalization theory as an improvement of the theory of technology as applied science. Thus, in their account of agricultural chemistry Wolfgang Krohn and Wolf Schäfer state:

> Our aim here is not to introduce a distinction between agricultural chemistry as a finalized science and applied science, but rather to offer a more precise meaning for the vague notion of 'applied science'. The term 'applied science' gives the misleading impression that goal-oriented science simply involves the application of an existing science, rather than the creation of a new theoretical development. This in turn feeds the misconception that pure science is superior to applied science. [Krohn and Schäfer, 1983, p. 46]

One of the main aims of the finalization theory is to establish at which stages of scientific development finalization is possible and fruitful. For this purpose, it includes an account of scientific development that makes use of, but also substantially expands on, Thomas Kuhn's model of scientific development. Although it is not generally realized, Kuhn advocates a strongly internalist view.

> For a scientist, the solution of a difficult conceptual or instrumental puzzle is a principal goal. His success in that endeavour is rewarded through recognition by other members of his professional group and by them alone. The practical merit of his solution is at best a secondary value, and the approval outside the specialist group is a negative value or none at all. [Kuhn, 1970, p. 21]

The finalization theory also starts from a rather strict internal-external distinction, but then goes beyond a Kuhnian internalism by arguing that an interaction between external or societal goals and interests and internal or cognitive goals and interests is possible, and even to some extent necessary, at a certain stage of the development of scientific disciplines. The theory focuses on the disciplines of the natural sciences and claims that these sciences pass through three successive stages. First, there is the explorative stage, which bears some resemblance to Kuhn's pre-paradigmatic stage. At this stage, a well-developed domain-structuring theory is not (yet) available, and research methods are primarily empirical and classificatory rather than theoretical and explanatory. The next, the paradigmatic stage is guided by a general theory that structures the field of phenomena and directs the way they should be investigated. As in Kuhn's normal science, the aim is the empirical and conceptual articulation and validation of the central theoretical ideas. These second-stage developments may lead to 'closed theories', a notion adapted from physicist Werner Heisenberg and explained as follows:

> In general three things can be said of a closed theory ...: firstly, it will possess sufficient conceptual material to capture a particular field of phenomena; secondly, its validity will at least be proven for a number of instances; and thirdly, there are good reasons to expect that its validity extends to the whole category of phenomena in question. [Böhme *et al.*, 1983, p. 148]

Because these are quite demanding criteria, which will not always be met in actual scientific practice, the authors introduce the weaker notion of theoretical maturity for cases where the theories are not strictly closed but still possess a substantial measure of comprehensiveness and stability. Hence the claim of the finalization theory is that, from an internal-scientific perspective, theoretically mature disciplines are more or less complete. Nevertheless, they can be developed further into a third, or postparadigmatic, stage, in which they become oriented towards external goals and interests through the development of 'special theories' (sometimes also called 'theoretical models') for the purpose of realizing certain technological applications. It is at this stage that science becomes finalized. In contrast to Kuhn, at this stage the 'practical merit' and the 'approval outside the specialist group' are primary values, and yet realizing this merit requires the development of genuinely new theoretical knowledge.

The finalization theory has been developed in close interaction with case studies of important episodes in several disciplines (see Part I of [Schäfer, 1983]). In physics, the articulation of classical hydrodynamics into a variety of special theories of fluid dynamics for the development of airplanes has been studied. In chemistry, the relationships between nineteenth-century organic chemistry, the special area of agricultural chemistry and the production of artificial fertilizers has been investigated. And in biomedical science, the development of molecular biochemistry into special theories of carcinogenic processes with a view to the production of appropriate drugs has been scrutinized. The authors themselves conclude that their theory applies best to the discipline of physics. Its appropriateness for the other disciplines is judged to be (far) less straightforward, the major problem being the applicability of the notion of theoretical maturity.

The theory of finalization was proposed more or less simultaneously with, though independently of, the strong program in the sociology of scientific knowledge.[10] Although both approaches share an emphasis on the significance of external factors, there are also important differences between the finalization theory and the sociology of scientific knowledge. First of all, the former, in contrast to the latter, does not claim that scientific truth depends on external goals and interests. Furthermore, the finalization theory focuses on *conscious* or *intentional* external influences in a science policy context. Hence, the theory includes an explicit evaluative and normative component: although orientation towards external goals and interests is feasible in the explorative and, to some extent, even in the paradigmatic stage, the best and most fruitful way to exploit the technological potential of the sciences is through the finalization of mature scientific theories in their postparadigmatic stage.

During the 1970s and early 1980s, the finalization theory sparked an extensive and at times acrimonious debate (see the bibliography in [Schäfer, 1983, pp. 301-306]). This debate was both philosophical and political in nature,[11] but it was primarily restricted to Germany.[12] Thus far, in Anglo-Saxon philosophy of science the relationship between science and technology has been a neglected issue anyway (cf. [Ihde, 1991; 2004]). Within the recently rising philosophy of the technological sciences, however, the theory of finalization constitutes a worthwhile topic for studying the intersections between science, technological science and technology. In the remainder of this section, I will discuss the merits and problems of this theory.

A first merit of the theory is that it provides a significant extension of Kuhn's account of the development of science. It shows that older paradigms are not, or not necessarily, discarded after the advent of a successor, since they may be further developed through processes of finalization. Furthermore, the theory takes into account the obvious importance of external goals and interests, especially since the second half of the nineteenth century, and thus goes beyond Kuhn's inadequate internalist approach. What is particularly insightful is the subtle way in which these internal and external factors are shown to be interwoven. Even if finalized science is not autonomous, the external goals and interests do not operate as purely extrinsic impositions. Instead, they are transformed and internalized as cognitive constraints on, or specifications of, the special technological theories that need to be developed on the basis of a mature scientific theory. For instance, in nuclear fusion research scientists try to develop a special theory of plasma physics that will ultimately enable the construction of a stable and reproducible nuclear fusion

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[10] For a detailed exposition of this program, see [Barnes *et al.*, 1996].

[11] Politically, the proponents of the finalization theory were accused of promoting socialist state regulation and criticized for advocating the societal steering of science at the expense of its academic freedom.

[12] The philosophical claims of the finalization theory have also been widely discussed in The Netherlands. See, e.g., [Nauta and De Vries, 1979; Zandvoort, 1986].

reactor (see [Böhme *et al.*, 1983, pp. 154-156]). Technically, this means that only such processes are considered for which the product τ of the containment time and the temperature of the plasma exceeds a certain minimum value τ_0. Thus, the external technological goal of providing nuclear fusion energy in a controlled, safe and economically efficient way has been transformed and internalized as a specific guideline for scientific theorizing. It tells the researchers to focus their theoretical work only on such constellations of plasma and container for which $\tau > \tau_0$.

Furthermore, the finalization theory convincingly demonstrates that technological science develops genuinely original knowledge, a point that is also emphasized in many recent contributions to the philosophy of the technological sciences (see, e.g., [Boon, 2006]). Technological knowledge is not, as seems to be implied in Bunge's view of technology as applied science, a mere application of existing scientific knowledge.

Another important aspect of the finalization theory is the attempt to provide a differentiated account of the relationship between external-societal and internal-cognitive factors in the development of the sciences. Whether fully successful or not, the theory at least attempts to make explicit the specific conditions under which external steering of science is possible and fruitful. In this respect, it favorably contrasts to some more recent approaches, in particular to the now fashionable idea of a linear historical succession of a 'Mode 1' science, which is largely autonomous and disciplinary, followed by a 'Mode 2' science, which is primarily focused on, and guided by, technological, economic and socio-political contexts of use.[13]

Finally, at least some of the proponents of the finalization theory foster a commitment to a science 'in the public interest'. Finalized science, they claim, should not evolve in a power-driven, Darwinist way, but be guided by procedures of explicit and democratic deliberation about the rational acceptability of the means and ends of proposed technological developments. Again in contrast to the Mode 1/Mode 2 approach mentioned above, this acknowledgment of normative issues is important, even for those who do not share the specific position of the advocates of the finalization theory. Moreover, given the problematic consequences of the rapidly increasing commercialization of science over the past twenty-five years, the notion of a science in the public interest is still as timely as ever (see, e.g., [Krimsky, 2003]).

Next to these merits, however, the finalization theory has several problematic characteristics and implications. As we have seen, the authors themselves already confronted the problem of the definition of a closed theory and especially its application to the history of science. They concluded that the applicability of the theory to disciplines other than physics is unclear. Thus, in the case of nineteenth-century agricultural chemistry, there was no closed theory available and the authors of the case study fall back on watered-down notions such as 'relative theoretical maturity' and 'methodological maturity' [Krohn and Schäfer, 1983]. But even cases

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[13] See [Gibbons *et al.*, 1994]; for a critical review, see [Weingart, 1997].

from physics are not straightforward. An interesting case would be to investigate the recent ‘finalization’ of climate science in the face of the human-induced greenhouse effect. It is by no means obvious that this research is building on a closed, or mature, theory of the dynamics of the entire climate system (see [Petersen, 2006, Chaps. 5 and 6]).

The finalization theory rightly claims that technological science develops genuinely new knowledge. But whether its characterization of this knowledge exhausts the knowledge generated in the technological sciences is another matter. According to the finalization theory, technological knowledge is developed on the basis of closed or mature scientific theories. In general, however, such knowledge will only be a part of the knowledge required for the design, production, use or maintenance of technological artifacts or systems (see also Houkes' chapter in this Volume, Part II). For instance, a fluid dynamics model of the boundary layer and the concepts of lift and circulation — as discussed in [Böhme, 1983] — does not yet permit the design and manufacture of a real airplane, let alone the realization of the entire technological system of air transportation.[14] This obviously limits the value of the finalization theory for a philosophy of technology and the technological sciences.
indent Related to this is a theory-dominant view of (natural) science. Although the significance of experimentation is acknowledged in principle, the finalization theorists' view of the technological sciences is still thoroughly theory-biased. It is theory formation which is seen as the core of scientific development and as the royal road to the fruitful exploitation of science for practical purposes. In the meantime, however, many authors in the philosophy of scientific experimentation (see note 2) have demonstrated that experimentation has a life of its own and is not limited to the testing of pre-existing theories. For this reason, it is also incorrect to identify the notion of a paradigm with that of a theory (see also [Rouse, 1987, Chap. 2]). Moreover, seeing observational and experimental science as merely preparadigmatic overestimates the role of explanatory scientific theories, especially in the technological sciences.

Finally, the finalization theory exhibits certain questionable modernist characteristics. It entails a belief in the possibility of a universally valid model of scientific development. As such, it cannot do justice to the diversity and richness of the actual development of the (technological) sciences. Moreover, the theory strongly suggests an overoptimistic belief in social progress through the employment of science. As such, it does not show great awareness of the fact that (technological) science may itself be a source of social problems. One does not need to be a radical postmodernist to see the problematic character of these two beliefs.

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[14] For more on the systemic character of technology, see [Hughes, 1987; Radder, 1996, Chap. 7].

5 EXPERIMENT AND THE SCIENCE-TECHNOLOGY RELATIONSHIP

As we have seen, the finalization approach represents a form of theory-dominant philosophy of science. In fact, however, a focus on experimentation provides a quite natural starting-point for studying the science-technology relationship. To mention just one example: the method of systematic parameter variation pioneered in the eighteenth century by John Smeaton to scrutinize and test the working and efficiency of waterwheels [Channell, this volume, Part I] plays an important part in both experimental science and in engineering and technological research. Hence, in this section I will review some philosophical accounts of experimentation as a crucial link between science and technology.

In his early philosophy, Jürgen Habermas has discussed the relation between technology and the natural sciences in some detail (see [Habermas, 1971; 1978]). He conceives of these sciences as intrinsically related to technology. Like logical positivism, Habermas sees observation as the basis of science, but he emphasizes that what counts in science is never the single, isolated observation but only the observation that can be reproduced by other scientists. Thus, his actual focus is on reproducible observations and, more generally, on predictive empirical laws. Such laws, Habermas claims, cannot be interpreted as reflecting a human-independent reality, since their universal validity depends on the possibility of active intervention and control of the empirical situation by human beings. Put differently, the epistemic warrant for the empirical law ‘whenever x, then y’ is provided by the practical result that ‘whenever we do x (under controlled conditions c), then we can bring about y’. This intervention and control is enabled through human, instrumental action. In this way, a ‘technical interest in prediction and control’ guides the production of natural scientific knowledge. The very constitution of experience on the basis of instrumental action orients science towards the technological application of the knowledge acquired. Prediction and control through intervention are the essential characteristics of the empirical laws of science and as such these characteristics foreshadow its technological application.

In science, instrumental action takes the form of experimental action. Hence, experiment constitutes the basic link between science and technology. Following Charles Peirce, Habermas explains the notion of a scientific experiment as follows:

> In an experiment we bring about, by means of a controlled succession of events, a relation between at least two empirical variables. This relation satisfies two conditions. It can be expressed grammatically in the form of a conditional prediction that can be deduced from a general lawlike hypothesis with the aid of initial conditions; at the same time it can be exhibited factually in the form of an instrumental action that manipulates the initial conditions such that the success of the operation can be controlled by means of the occurrence of the effect. [Habermas, 1978, p. 126]

This quotation clearly expresses the intrinsic relation between predictive scientific knowledge and controlled technological action and production that is characteristic of Habermas's early philosophy. In his further development, however, Habermas changed his views on this subject, in particular by incorporating the theory-ladenness of observation and more in general by acknowledging the relative autonomy of theoretical argumentation in science. Thus, the focus of his philosophy shifted to the subjects of argumentation and communication. As a consequence, he did not develop his rather schematic view of experimentation as a significant link between science and technology. Hence, it is worthwhile to take a closer look at this subject on the basis of a more detailed account of scientific experimentation.[15] The purpose of this discussion is to employ this account to illuminate important aspects of the relationship between science and technology.

A characteristic feature of experimental science is that access to its objects of study is mediated through apparatus (in the form of instruments and/or other equipment or devices).[16] In an experiment, we (try to) bring about a correlation between an object of study and some apparatus, and to draw conclusions about that object on the basis of a 'reading' of some features of the apparatus. As Habermas correctly argues, scientific experiments are meaningful only to the extent that our intervention and control produces a correlation between object and apparatus which is stable and reproducible. An important necessary condition of experimental stability and reproducibility is the appropriate control of the actual and possible interactions between the experimental (or object-apparatus) system and its environment.[17] It is useful to distinguish three types of such interactions: the *required* interactions, which enable the object-apparatus system to behave according to its design; the *forbidden* interactions, which might disturb the intended experimental processes; and the *allowed* interactions, which are neutral with respect to the planned course of the experimental system and thus neither enabling nor disturbing. To realize a stable and reproducible experimental system, the required interactions need to be produced and maintained, the forbidden interactions need to be eliminated or prevented from taking place, while the allowed interactions do no harm and hence do not need to be controlled.

For instance, if a particular experimental design requires a low temperature of, say, 100K, then we need to produce a starting temperature of 100K and we need to control the heat flow between experimental system and environment in such a way that the system stays at this temperature during the entire course of the experiment. Furthermore, if an impact of electromagnetic waves could disturb the intended experimental processes, we have to prevent such waves from interfering with the object-apparatus system during all experimental runs. Finally, if the gravitational interaction between system and environment does no harm, we do not have to control for it. The presence of required and allowed interactions

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[15] The present sketch of this account draws on analyses in [Radder, 1988, Chapter 3; 1996, Chapter 6; 2003]. Additional detail, including a characterization of the implied notion of 'technology', can also be found in Radder's chapter in this Volume, Part V.

[16] For discussions and classifications of scientific apparatus, see [Harré, 2003; Baird, 2003; Heidelberger, 2003].

[17] Of course, this control is not sufficient, since the object-apparatus system itself may be internally unstable and irreproducible.

implies that successful experimentation does not necessitate a completely isolated system, that is, a system that does not at all interact with its environment. Materially realizing such a system would be very difficult and probably even impossible, given the ubiquity of gravitational and/or electromagnetic interactions.

Of course, in actual scientific practice we may not always, or not yet, know which interactions are required, forbidden or allowed; or we may be wrong in our assessment of these interactions. Anyway, an important part of the aim of experimentation is to get to know which interactions are enabling, disturbing or neutral. Two features of such processes of acquiring experimental knowledge are directly relevant to the issue of stability and reproducibility. First, what is seen to be required, forbidden or neutral will depend on the theoretical interpretation of the experiment in question. Types of interaction that are claimed to be theoretically impossible (e.g., telepathic influences or signals traveling faster than light) will be irrelevant and do not need to be taken into account. The same applies to interactions that are possible (and may be present) but are claimed to be inconsequential to the plan and aim of the experiment (e.g., the 'impact' of daylight in measuring the temperature of a fluid) and hence classified as 'allowed'. Yet, we should note that such claims may be contested by other experimenters or overthrown by later developments. Second, controlling the relevant interactions is, in practice, not only a matter of exercising the required material control, but it also demands a social discipline and control of all the people that have, or might have, an impact on the material realization of the experiment. After all, it is these people who play, or might play, a critical role in the processes of producing or securing the enabling conditions and eliminating or preventing the disturbing conditions. In addition to these two features, there may also be social or ethical reasons for the need to control further interactions between an experimental system and its environment. For instance, impacts of an experimental system on the environment that could endanger the safety of the experimenters or of other human beings are generally seen to be undesirable and hence they need to be prevented. Thus, the necessary control of the (desirable and undesirable) influences and disturbances between the object-apparatus system and its environment exhibits important theoretical, material and social features of scientific experimentation.

Next, this analysis may be used to discuss and assess the science-technology relationship in two different ways. Just like experiments, working technologies need to be stable and reproducible, while the control of the relevant interactions between the technological system and its environment constitutes a necessary condition for achieving this goal. Again, we may distinguish between required, forbidden and allowed interactions. Thus, *in a conceptual-theoretical sense*, the successful realization of a technological system poses similar requirements as the successful realization of an experimental system. The system-environment interactions that enable the technological system to behave according to its design need to be produced and maintained, the interactions that might disturb the intended technological processes need to be eliminated or prevented from taking place, while the interactions that are inconsequential to the stable and reproducible working of the technological system may be ignored.

Furthermore, *in an empirical sense*, materially realized experimental substances, devices or processes may be, and often are, exploited as (part of) technological systems. A particular piece of experimentally developed electrical circuitry may be used to fulfill a certain function as part of a larger technological system, for instance a computer. Or an organism that has been genetically modified in a biology laboratory may get exploited in particular agricultural technologies. As in the case of their scientific counterparts, such 'experimental technologies' are supposed to exhibit a certain measure of stability and reproducibility, and hence the relevant system-environment interactions need to be controlled. Materially and socially, however, experimental systems and the corresponding experimental technologies will usually be quite different for two reasons. First, technologies are typically required to remain stable and reproducible for a much longer period and in many more places. That is to say, the technology is supposed to function properly on a much larger spatiotemporal scale than its laboratory counterpart. Second, and related to the first reason, the environments in which the experimental technologies are expected to function may be quite different from the average laboratory environment.

For these reasons, we cannot assume that a successfully realized experiment guarantees the success of the corresponding experimental technology.[18] A nuclear fusion device that works well in the laboratory by no means provides us with a stable and reproducible fusion reactor that can be effectively exploited for controlled energy production. Similarly, a successful in vitro test of experimental AIDS vaccines does not necessarily entail a successful in vivo therapy for AIDS patients.[19] Time and again, however, scientists from all kinds of disciplinary backgrounds have made such unwarranted leaps, either because of their inadequate view of the relation between science and technology or simply to flatter their funding agencies for the purpose of acquiring additional financial support.

In this respect, it is interesting to look back briefly at the finalization theory. According to this theory, during the paradigmatic stage so-called 'transfer research' is possible. This research includes the systematic 'scaling-up' of laboratory experiments into industrial processes. Apparently, this scaling-up is seen as the unproblematic application of existing knowledge and as not requiring specific further research. Hence it is claimed that, in the paradigmatic stage, science policy can only promote research, but it cannot substantially guide it in novel directions [Böhme *et al.*, 1983, pp. 152-153]. As my more detailed examination of the relations between experimental and technological science has shown, however, these 'scaling-up' processes are by no means straightforward. They require a

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[18] Hence, the twofold meaning of 'experimental technology' as 'resulting from experimental research' and as 'still being tentative'. See also the notion of 'society as a laboratory' in [Krohn and Weyer, 1994].

[19] See [Radder, 1996, Chaps. 6 and 7], where these issues and relevant cases, such as nuclear power production, entomological pest control and agricultural biotechnology, are examined in detail.

substantial additional study of the processes that will, or may, occur at the larger temporal and spatial scales and of the new environments in which the technologies are expected to function. An important aim of such studies is to generate new knowledge about the stable and reproducible working of these technologies at the required scales and in the intended environments.

The account of the science-technology relationship discussed in this section engenders two critical questions, both of which are crucially important regarding the social governance and normative assessment of scientific and technological projects. First, there is the factual question of whether an intended extension of a successful experiment to a stable and reproducible experimental technology can be reasonably believed to be feasible. The larger the spatial or temporal extension of the intended technological system, the more pertinent this question will be. Second, there is the normative question of whether the controlled material and social world that is needed to guarantee the stability and reproducibility of the technological system is a normatively desirable world. If one or both of these questions are answered in the negative, the only reasonable option is not to realize this particular technology. In my chapter in this Volume, Part V I will come back to these questions and discuss them more fully.

6 SCIENCE AS TECHNOLOGY

The fruitfulness of seeing experimentation as a central link between science and technology might tempt us to conceptualize science and technology as substantially, basically, or even essentially, similar. And, indeed, philosophical accounts of the science-technology relationship repeatedly advocate such a conception of ‘science as technology’. Illustrations can be found in the work of Martin Heidegger, (the early) Jürgen Habermas, Peter Janich and Srđan Lelas. More recently, comparable views in terms of the notion of technoscience have been developed by Donna Haraway, Bruno Latour, Don Ihde and Karl Rogers, among others. This notion of technoscience is claimed to capture the crucial similarities between science and technology. First, it posits the primacy of practice: both scientists and engineers or technologists are centrally involved in practical processes of intervention, negotiation and construction. Furthermore, in contrast to more traditional accounts of the science-technology relationship (such as Bunge’s applied-science account), a technoscientific approach highlights the importance of materiality — that is, the material artifacts, interactions and procedures — for both science and technology. Finally, this approach emphasizes the fact that, in the course of the twentieth century, science has increasingly become ‘big science’ and as such it has acquired — and it does require — the format of an industrial organization. By way of example, consider Bruno Latour, who rejects any basic distinction between science and technology by emphasizing the constructive and adversarial nature of both.

> It is now understandable why, since the beginning of this book, no distinction has been made between what is called a 'scientific' fact and what is called a 'technical' object or artefact. The problem of the builder of 'facts' is the same as the problem of the builder of 'objects': how to convince others, how to control their behaviour, how to gather sufficient resources in one place, how to have the claim or the object spread out in time and space.[20]

In this section I address the views of Srđan Lelas [1993; 2000], who has developed the science-as-technology account in more philosophical detail. Lelas opposes his account to contemplative, or *theoria*, views of science. Such views, he claims, separate epistemology from ontology and semantics. That is to say, observation and experiment may be required for ascertaining the truth of theories but as such they are taken to be mere means. After all, whether or not theories are true is supposed to be exclusively a matter of their correspondence to a human-independent reality. Hence, when theories are true, all traces of the way we have found them, through interacting with and intervening in the world, become irrelevant and should be erased. That is to say, ultimately observation and experiment are eliminable.

From his science-as-technology perspective, Lelas raises two kinds of objections to such *theoria* views of science. First, he argues that experimentation, as the design and production of artifacts, involves an interaction and interference with nature, and he notes that scientific observation shares a number of crucial features with experiment [Lelas, 1993]. Through processes of experimentation and observation, which involve the making of artifacts through implementing an idea, science discovers because it invents. In Lelas's Heideggerian phrase, 'nature is at once revealed and produced'. The two sides of this process — revealing and producing nature — cannot be separated, as it is done in the *theoria* account. Lelas concludes that the productive activity of observing and experimenting, which is essentially technological in nature, constitutes an indispensable element of the ontology of science. For this reason, the significance of observation and experimentation goes far beyond their role as instruments for testing the truth of theories.

The second objection to *theoria* views has to do with the function and meaning of theories. Like Janich and Latour, Lelas claims that the meaning of theories cannot be divorced from their function in experimental or observational processes. Theories should be experimentally testable and this requires that the route from theory to experiment should be mapped out by the theory itself.

> Theory [cannot] be treated as a mere instrument for calculation and prediction of the experimental outcome. It is much more than that. It is *an instrument of design*, and being that, it encompasses both ontology and technology. A theory can be considered as a condensed set of instructions of how to build an experimental apparatus, or, better,

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[20] [Latour, 1987, p. 131]. He does, however, allow for some differences in degree, in the sense that scientists more often focus on new and unexpected procedures or objects, while technologists are more often engaged in coordination and consolidation of existing activities or artifacts.

> how to guide the production of experimental artefacts. [Lelas, 1993, p. 442]

Hence, the essence of scientific theories is not to be found in their abstract conceptual or mathematical structures as such, but rather in the translations and interpretations which connect theoretical concepts or statements to the practice of observational and experimental action and production.

In his book *Science and Modernity*, Lelas develops these views about science and technology and embeds them in a comprehensive and (broadly) naturalist theory of the processes of human cognition, of the rise of (modern) science and of the nature of scientific knowledge. For instance, from an evolutionary, biological perspective, humans prove to be 'prematurely born, retarded and unspecialized mammals'. In order to survive they need to be able to adapt to a large variety of selection environments. For this purpose, technology is seen to be particularly important.

> Artefact making is not the only component of human existence; it covers only one aspect of the relationship between humans and nature. Mind/brain, language and institutions are the others. *Together* they constitute what we usually call *culture*. But technology is the essential part of it; it is the part that completes the physical exchange between humans as living systems and their physical environments. [Lelas, 2003, p. 112]

Lelas goes on to explain the rise of science as having been enabled by the 'urban revolution' in ancient Egypt, the Middle East, India, China and the Americas. Yet *modern* science, which emerged from the sixteenth and seventeenth century onwards, required two important further developments: first, the economically motivated doctrine and practice of the human mastery of nature; and second an ever increasing transfer of human activities and functions to technological artifacts. This leads him to the aforementioned claims that experimentation constitutes the most important innovation of modern science and, more specifically, that even scientific theory is, ultimately, about making.

In concluding this section, I will briefly assess Lelas's science-as-technology account. His general theory of science and modernity primarily deals with the natural and cultural preconditions and contexts of (modern) science. The theory is thoughtful and intriguing, and Lelas's book contains a wealth of interesting discussions, but a more detailed review is really beyond the scope of the present chapter (for this, see [Radder, 2002]). Hence, I will limit myself to some more specific remarks on the relationship between science and technology.

On the basis of the discussion in the previous sections, in particular Section 5, we may conclude that Lelas's emphasis of the significance of the action and production character of experimentation is fully justified. Moreover, extending this account from experimentation to scientific observation has much to recommend it. As we have seen, Lelas endorses the more specific claim that theory plays a role not just in making predictions of experimental results but much more generally as an instrument guiding the entire process of the production of experimental artifacts. Although some authors have claimed that theory-free experimentation is possible and regularly occurs in the development of science, a closer look at scientific practices reveals that Lelas's claim can be maintained, if it is more specifically construed as stating that the performance and understanding of experiments depends on a theoretical interpretation of what happens in materially realizing the experimental process [Radder, 2003].

In spite of this, the general reductionist view that science is, basically, technology cannot be upheld. Consider the claims that there is a 'full continuity between high scientific theory and the skills of the experimenter' and that 'a theory can be considered as a condensed set of instructions of how to build an experimental apparatus' [Lelas, 1993, pp. 441-442]. In this respect it is important to make a distinction between the 'high theory' of the object under study and the theoretical interpretation of the entire experimental process. Generally speaking, the former tells you something about the experimental process, but in no way can it be said to guide the production of experimental artifacts. For instance, as we have seen in Section 3, the high theories of quantum physics do not even suffice to construct and use theoretical models of laser phenomena, let alone tell us how to build such devices. A further problem of Lelas's science-as-technology account is the fact that scientific theories have a meaning that transcends the meaning of the particular experiments that have thus far been used to test these theories. In as far as this account overlaps with the operationalist theory of meaning, it is vulnerable to the well-known criticism that this theory entails an unfruitful proliferation of theoretical concepts and that it neglects the systematic significance of theoretical frameworks [Hempel, 1966, pp. 88-100].

That theories have such a 'surplus' meaning can also be seen by analyzing the notion of experimental reproducibility in more detail. In Section 5 I employed the notion of reproducibility in an undifferentiated way. In fact, however, reproducibility is a rather complex notion. First, it is important to distinguish between the actual reproductions and the (claimed) reproducibility of an experiment; in addition, we need to ask *what* has been reproduced, or is (claimed to be) reproducible, and *by whom*? [Radder, 1996, Chaps. 2 and 4]. In the present context, the relevant distinction is that between the (claimed) reproducibility of the entire experimental process and the (claimed) reproducibility of the result of this process. An important point of this distinction is that the latter notion, which is also called replicability, implies the reproducibility of the result through a number of possibly radically different experimental processes. Both notions play an important role in scientific practice. On the one hand, if an entire experimental process is reproducible, this fact will facilitate its technological use. For instance, the reproducible procedures of Justus von Liebig's experiments in organic chemistry definitely facilitated the technological production of artificial fertilizers (even if the full implementation of this agricultural technology, in line with the discussion in Section 5, required further research and additional knowledge). On the other hand, if the result of an experimental process is replicable, it may be considered in abstraction of the original experimental process through which it was produced thus far. This kind of abstraction constitutes a first step towards a wider *theoretical treatment and understanding* of the meaning and implications of this result. Suppose, for example, that certain reproducible experimental processes in a ruby crystal result in the production of a laser beam. If this result is replicable, it will make sense to abstract it from the specific processes in ruby crystals and to study the phenomenon of lasing from a more general, theoretical perspective.

This argument may be summarized by saying that theoretical concepts possess a nonlocal meaning, that is to say, a meaning that essentially transcends the meaning they have as interpretations of the local experimental processes to which they have been applied thus far. I conclude that the meaning and function of theories cannot be reduced to their guiding function in producing particular experimental artifacts. This conclusion undermines the core of Lelas's science-as-technology view, as well as the similar views of other philosophers, such as Latour, the early Habermas, Heidegger and Janich.[21]

7 CONCLUSION

In this chapter I have addressed the relationship between science and technology, primarily from a conceptual-theoretical perspective but with a keen eye for their actual practices. As we have seen in Section 2, strict definitions of (the aims of) science and technology, in the sense of one or two characteristics that constitute necessary and sufficient conditions, are hard to come by. All attempts to provide essentialist definitions of science and technology prove to be questionable (cf. [Mitcham, 1994] and Mitcham and Schatzberg's chapter in this Volume, Part I). What results from the preceding discussions is a more differentiated account in which science and technology exhibit both similarities and dissimilarities. Starting from an intuitive pre-understanding that needs to be qualified or modified by empirical studies, science, technology and their relationship may be characterized by these similarities and dissimilarities, or more precisely by certain patterns that they share and by further patterns that are more typical of the one than of the other.

Thus, as explained in Section 2, the intuitive idea that the design of material things and processes might constitute an essential contrast between science and technology needs to be adjusted to a pattern of similarity and dissimilarity: since design is a pervasive characteristic of observational and experimental science, the contrast merely applies to theoretical science. Section 5 shows the significance of controlling the interactions of both experimental and technological systems with their environment. At the same time, the typical dissimilarities in spatiotemporal scale and in the nature of the environment entail a number of important cognitive,

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[21] For an extensive historical review and an intriguing cultural critique of the science-as-technology interpretation, see [Forman, 2007], who argues that the sudden rise of this interpretation (circa 1980) is a major sign of a general turn from modernity towards postmodernity.

material and social differences between science and technology. Similarly, Section 6 demonstrates that the notion of reproducibility applies both to science and technology. But again, an important dissimilarity arises as well, since technology focuses primarily on the reproducibility of the entire technological process while scientific practice exhibits an additional emphasis on replicability and abstraction. Thus, this line of reasoning goes against the reduction of science to technology and argues for the legitimacy of a theoretical science that is not, or at least not immediately, technologically useful.[22]

Section 3 shows that Mario Bunge's account of technology as applied science is fundamentally flawed. The claimed epistemological subordination of technology to science and the alleged insignificance of practical craft work do not fit exemplary episodes of scientific and technological development. A remaining dissimilarity is a greater emphasis (in technology) on realizing external, societal objectives. Yet, even this claim needs a twofold qualification. First, such objectives are, so to speak, the distal, collective aims that need not have an immediate impact on the proximate aims (and hence on the 'outlook and motivation') of the individual technologists. Furthermore, as I emphasized in Section 2, basic science — in particular contemporary basic science — may just as well be oriented towards such distal aims.

More generally, in agreement with the finalization theory discussed in Section 4, the notion of 'application' has become too closely linked to views similar to those of Bunge. Hence, to keep using this notion seems to be ill-advised. Instead, I suggest the locution 'the uses of science'. Of course, simply replacing 'applying science' by 'using science' is not very helpful either. We need to specify this phrase in a fourfold way. That is to say, we need to pose and answer the following questions: which aspects of science are used, with *which further means*, with *which technological results*, and for *which purposes*?

As for the different 'aspects of science', we have seen that not just fundamental laws may be used, but also more local models, and not only theoretical tools but experimental or observational results and techniques as well. What we have also seen, especially in Sections 4 and 5, is that using science requires 'further means' in the form of substantial additional work to bridge the gaps between scientific and technological problems, results and contexts. Major examples of such further means are the development of genuinely new technological knowledge and the substantial research needed to transpose the results of successful laboratory experiments to stable and reproducible technological systems. This immediately implies a differentiation in 'technological results', which may be technological knowledge, technological methods and procedures, or technological artifacts and systems, including the social knowledge and social conditions needed for their stable and reproducible realization. Finally, there are the 'purposes of using science' in tech-

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[22] Since patentable technologies need to be 'industrially applicable', that is, technologically useful, the argument has significant implications for the justifiability of current practices of academic patenting [Radder, 2006, Chap. 16]. See also van den Belt's chapter in this Volume, Part VI.

nological projects. These purposes may be broad, societal aims, but there may also be more limited, scientific ends. Since the advancement of science is often dependent on the availability of cutting edge technological instrumentation, the end of making new instrumentation may be to feed it immediately back into the development of science itself.[23] Of course, science is also often used with a view to 'broader societal aims'. A satisfactory account of the nature and legitimacy of such aims would require much more differentiation. After all, there is a big difference between the case of a single firm wishing to produce a specific artifact for enhancing its own profit or the case of the World Health Organization urging biomedical scientists to develop more medical knowledge and technology for the purpose of a worldwide struggle against malaria. Thus, philosophical accounts of the relationship between science and technology, as discussed in this chapter, should be complemented by equally differentiated accounts of the social and normative issues that are intrinsic to the uses of science in technology.[24]

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[23] Just think of the impact of particle accelerators and detectors on the history of twentieth-century microphysics documented in [Galison, 1997]; other examples are the scientific uses of multi-purpose research technologies, such as the ultra-centrifuge, discussed in [Shinn and Joerges, 2002].

[24] See the chapters on normativity and values in Part V of this Handbook.

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