1 SCIENCE, TECHNOLOGY, AND THE SCIENCE-TECHNOLOGY RELATIONSHIP

A CRITICAL ANALYSIS OF THE COMMODIFICATION AND THE COMMON good of science needs to include a detailed account of how science relates to technology. Therefore, this chapter discusses and assesses a range of philosophical accounts of the science-technology relationship.[1] The discussion is meant to cover a variety of scientific disciplines, even if the examples show some emphasis on the natural sciences.[2] In discussing how these disciplines relate to technology, we need to take into account the technological sciences. These include several application-oriented disciplines in addition to the engineering sciences, such as the information, medical, and agricultural sciences. Making such a direct link between technologies (in the stricter sense defined and discussed in chapter 2) and the technological sciences makes sense because these sciences focus on realizing incipient or future technologies. Accordingly, this chapter addresses a broad range of technological activities, such as research, design, production, use, and maintenance.

1. This chapter is a reedited and slightly expanded version of my essay "Science, Technology and the Science-Technology Relationship," which is a chapter in *Philosophy of Technology and Engineering Sciences*, edited by A. Meijers and published by Elsevier in 2009.
2. For a review of the role of the social sciences in technology and engineering, see Sørensen 2009.

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 we will see, different authors offer quite different answers to these two questions. The chapter begins by discussing some critical methodological issues of how to interpret and study our subject. Subsequent sections review several important views of science, technology, and their relationship: the idea of technology as applied science; the conception of the social and technological finalization of science; the claim that experimentation constitutes the central link between science and technology; and the account of science-as-technology, including the related notion of technoscience. The final section sums up the main conclusions about the science-technology relationship, especially those about the uses of science in technology.

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 both science and technology, we must ask how one should acquire a plausible definition of these notions. Closely related is the 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 the aims of each. Many authors claim that the aim of science is epistemic, that it is 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* notion of science and technology does not do justice to the richness and variety of actual scientific and technological practices. Alternatively, they advocate a *nominalistic-empirical* approach: go and see, and define science (and technology) as the practical activity that is called science (and 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 nonexplanatory, as in the case of taxonomical knowledge (see, e.g., Kwa 2011, chap. 8). 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.[3]

Furthermore, defining science as the search for theoretical, explanatory knowledge presupposes a specific philosophical interpretation of science, which is not universally accepted. Bas van Fraassen (1980) argues that explanation is merely a pragmatic aspect of science, and he defines the aim of science as the development of theories that are empirically adequate (rather than true). Patrick Heelan (1983) also emphasizes the primacy of perception, although his notion of perception differs significantly from Van Fraassen's account. 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 (see Layton 1974; and Houkes 2009). Specifically, it is design knowledge that is claimed to have a prominent place in technology. In the technological sciences, this design knowledge is often of a general nature (Kroes 2009).

However, this definition of technology (with or without the addi-

3. See, for example, Janich 1978; Hacking 1983; Gooding 1990; Galison 1997; Lange 1999; Radder 2003a; and Baird 2004.

tion of design knowledge) does not give us a strict demarcation between science and technology. This is because designing and constructing material things or processes, including the generation and utilization of design knowledge, is an ordinary feature of observational and experimental science.[4] 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). These observational and experimental practices constitute a significant aspect of scientific disciplines. Thus, in contrast to what Edwin Layton (1974), Peter Kroes (1992), and many others claim, design (knowledge) and construction do not demarcate technology and engineering from science. The same conclusion applies to the attempt to base a demarcation argument on the contrast between prescription and description. Along these lines, Wybo Houkes (2009, 342) suggests that the recommendations and requirements that can be found in the use plans for technological artifacts may be specific to technology.[5] However, this argument overlooks the fact that similar prescriptive recommendations and requirements can be found in the many scientific practices aimed at realizing stable and reproducible observational or experimental processes.

What can we 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 toward its potential usefulness for society at large. Even this suggestion needs to be qualified, however. First, should this social usefulness be explicit and obvious even at the start of a technological project? If so, some of the research done in industrial laboratories may not qualify as technological. For instance, research done between 1947 and 1972 at the Philips electronics laboratories did not always aim at immediate technological applications (De Vries 2005). But if social usefulness may also emerge in the course of a project, then quite a few projects in prima facie scientific research will also count as technological. Scientific research is often supported by funding agencies because of its contribution to the "knowledge base" of a society, and thus this research can be seen as practical and useful in the long

4. Even computational science has a material side and thus involves some design of material things or processes. See the analysis of the simulation laboratory in Petersen 2012, chap. 2.

5. A detailed review of this use-plan approach will be given in chapter 2.

run.[6] For this reason, present-day funding applications for scientific research projects have to be routinely justified also in terms of their possible technological and societal payoff.

Let us now take a closer look at the nominalistic-empirical strategy. This involves the empirical investigation of whichever activities 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 offering any evidence or reflection. But 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 "preunderstanding." Suppose we visit a site called the 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 PhD holders write articles. When we focus on the writing of articles as part of scientific pursuit, we apparently apply a certain preunderstanding of what counts as (the core activities of) science. Thus, Bruno Latour and Steve Woolgar (1979) characterize laboratory science according to its production of "inscriptions" (and not, for example, by 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 PhD holders eating lunch in the institute's canteen. Thus, the nominalistic-empirical approach presupposes some conceptual-theoretical interpretation of what constitutes science and technology, and the question of whether we can make this preunderstanding 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-Americans distinguish sciences and humanities, which in German are both termed *Wissenschaft*. In earlier centuries, the term "natural philosophy" denoted what is now called "physical science." And nowadays we speak of computer science and

6. See Tiles and Oberdiek 1995, chap. 4. In chapter 7, I return to the subject of the societal value of basic science.

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 assess 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, it will acquire some normative force. Activities that do not conform to the established characterization of science or technology should not be termed 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 preunderstanding of both science and technology, and an appropriate empirical model of the science-technology relationship needs to be based on a plausible interpretive preunderstanding. 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.[7]

Finally, the relationship between science and technology may also be studied from an *evaluative* perspective. How are science and technology evaluated and how should they be evaluated, both in themselves and as compared to each other, as well as regarding their epistemic and their social or moral value?[8] Although such questions crop up occasionally in this chapter, they will be addressed in more detail in the subsequent chapters of this book.

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7. For a more detailed discussion of several important aspects of the empirical relationship between science and technology, see Channell 2009.
8. For a comprehensive historical discussion of these important normative issues, see Forman 2007.

TECHNOLOGY AS APPLIED SCIENCE

A still-current view of the relationship between science and technology appears in the formula "technology is applied science." A classic account of this view has been presented by Mario Bunge (1966). 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" (329). Thus, it is the distinct aims of science and technology that differentiate one from the other. 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 that accurately describe (external or internal) reality and enable us to predict the course of events. The technologist, by contrast, uses scientific laws as the foundation for rules that 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, 330) claims that the different aims of science and technology are inferred from differences in the 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 these outlooks and motivations can in some way be "derived" or "reconstructed" on the basis of the activities of scientists and technologists. Thus, 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 a 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, such construction work usually requires specific craft skills (such as the grinding of the lenses or mirrors) that do not employ scientific theories but are based on effective, practical know-how and procedures. Bunge concludes that a functioning artifact, such as a 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 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—among scientists, policy makers, and the public at large, for example. Sometimes such views include an even stronger hierarchical evaluation in which 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.[9] To begin with, several scholars have criticized Bunge's approach on historical grounds. They claim that historical studies show that many important technological inventions and innovations came about independently, unrelated to scientific research and scientific theorizing. Well-known examples include steam engines, water-power devices, mechanical clocks, and metallurgical techniques (Laudan 1984; see also Channell 2009).

9. My focus will be on the "substantive" theories of natural scientists and engineers, that is, theories about the technological objects or processes themselves, thus leaving aside the "operative" theories of social scientists and technologists, that is, the social theories about technological action and organization. For discussions of the latter, see Sørensen 2009; and Houkes 2009.

Although these criticisms seem basically valid, they do depend on the precise interpretation of Bunge's version of the linear model of the science-technology relationship.[10] A flexible interpretation of Bunge's model would permit the following responses. First, many of the historical counterexamples are quite old, often dating to the eighteenth century and before. Thus they need not be taken as 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 view of technology as applied science, then it is by definition not a technology. The remaining issue thus pertains to the usefulness and relevance of such a 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, Bunge 1966, 329) 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.

I will not pursue this debate any further here but instead develop a different assessment of Bunge's technology-is-applied-science view. For this purpose, it is important to realize that his view 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 their objection is that technology has often developed independently, apart from these laws and theories. That is to say, they claim that the differences between science and technology are larger than Bunge assumes. Second, 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

10. For extensive critical discussions of the linear model, see the contributions to Grandin, Wormbs, and Widmalm 2004.

testable, fundamental theories and by accepting or rejecting these theories according to how they match the empirical data. This account suggests that separate, fundamental theories can be confronted more or less directly with the empirical data. In fact, however, scientific practice is much more complex. Fundamental theories, such as 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 then, this theory has been "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. An example is laser physics, which combines insights from both atomic and molecular physics and from quantum electrodynamics (see Bromberg 1986).

We are thus confronted not with two types of activities (theoretical and experimental) but three: the construction of fundamental theories; their development and specification so as to make possible actual empirical tests; and the design and performance of experiments to test the theories. The second type of activity (development and specification) requires the articulation of the fundamental theories, usually through extensive calculation and substantial model building.[11]

Two aspects of these processes of development and articulation are particularly relevant to the 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 and appropriate to particular types of experiment. Nancy Cartwright (1983, 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, limited to a few types of experimental phenomena. More-

11. See Böhme, Van den Daele, and Hohlfeld 1983; and Cartwright 1983, 1999. For the sake of argument I have, like 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.

over, 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 fundamental theories alone. Thus, what we see in practice is the use of a variety 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, such as when the value of parameters that cannot be calculated theoretically is determined by fitting 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 use of workable methods for testing the theories. Scientific practice routinely includes the application of convenient rules of thumb and intuitive models for solving different problems, making approximations based on mathematical or computational feasibility, and black boxing (part of) a system by fitting theoretical parameters to experimentally determined data. The crucial point is that these are exactly the kinds of procedures that are typical of technology, as Bunge himself argues. 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.[12] 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, 107–12).

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 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 experimen-

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

tation, it is immediately clear that this suggestion makes no sense. 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).[13] 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 later in this chapter, the stability and reproducibility of observational and experimental results that scientists 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; and Radder 1996).

The discussion in this section does not claim to provide an exhaustive assessment of the view of technology as applied science.[14] However, it should suffice in demonstrating that Bunge's hierarchical approach is questionable. A reconstruction of scientists' versus technologists' cognitive activities does not support the attribution of essentially different aims to one group or the other. Consequently, this way of demarcating science from technology proves to be difficult, if not impossible, and the same applies to substantiating 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 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 return to this issue and address the question of how science and technology may be related and differentiated on the basis of their similarities and dissimilarities.

13. In a later publication, Bunge (1985, 220) 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." In spite of this, he immediately adds that it is only explicit, science-based technology that is philosophically interesting and worth studying.

14. For further discussions and assessments, see Tiles and Oberdiek 1995; Cuevas 2005; Boon 2006; Koningsveld 2006; and Channell 2009.

TECHNOLOGY AS FINALIZED SCIENCE

During the 1970s a group of German scholars, called the Starnberg group, published an impressive series of articles and books about the finalization of science (see Schäfer 1983 and references therein). "Finalized science" denotes a particular stage of scientific development that is more or less consciously oriented toward external social goals and interests. The Starnberg authors themselves see their finalization theory as an improvement on the theory of technology as applied science. Thus, Wolfgang Krohn and Wolf Schäfer (1983, 46) state in their account of agricultural chemistry, "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." 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, the theory includes an account of scientific development that makes use of but substantially expands on Thomas Kuhn's model of scientific development. Although it is not generally acknowledged, Kuhn (1970b, 21) 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." 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 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 exploratory stage, which bears some resemblance to Kuhn's preparadigmatic 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 paradigmatic stage is next. It 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 conceptual and empirical articulation and validation of the central theoretical ideas. These second-stage developments may lead to "closed theories," a notion adapted from the 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, Van den Daele, and Hohlfeld 1983, 148). Because these are quite demanding criteria that will not always be met in actual scientific practice, the authors introduce the weaker notion of theoretical maturity for cases in which the theories are not strictly closed but still possess a substantial measure of comprehensiveness and stability. Thus, 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 toward 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's view, 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 Schäfer 1983, part 1). 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 have 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 contributors to the Schäfer (1983) volume 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.[15] 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. The theory thus includes an explicit evaluative and normative component: although orientation toward 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 Schäfer 1983, 301–6). This debate was both philosophical and political in nature, but it was mostly confined to Germany.[16] Politically, the proponents of finalization were accused of promoting socialist state regulation and criticized for advocating the societal steering of science at the expense of its academic freedom. Thus, the debate addressed, in part, issues similar to those of the recent debate on the commodification of academic research (discussed in chapters 3 and 4). Until recently, among Anglo-American scholars of philosophy of science the relationship between science and technology has been a neglected issue anyway (see Ihde 1991, 2004; and Radder 2015). Within the ascendant field of philosophy of the technological sciences, however, the theory of finalization constitutes a worthwhile topic for studying the connections between basic science, application-oriented science, and technology. In the remainder of this section, I will discuss the merits and problems of this theory.

One merit of the theory is that it provides a significant extension of Kuhn's account of the development of science. It shows that older par-

15. For a detailed exposition of this program, see Barnes, Bloor, and Henry 1996.
16. The philosophical claims of the finalization theory have also been widely discussed in the Netherlands. See, for example, Nauta and De Vries 1979; and Zandvoort 1986.

adigms 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; it 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 make possible the construction of a stable and reproducible nuclear fusion reactor (see Böhme, Van den Daele, and Hohlfeld 1983, 154–56). Technically, this means that the only processes considered are those 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 application-oriented sciences develop genuinely original knowledge, a point that is also emphasized in many recent contributions to the philosophy of the engineering 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 sociopolitical contexts of use.[17]

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. This acknowledgment of such normative issues is important, even for those who do not share the specific position of advocates of the finalization theory. Moreover, given the problematic consequences of the rapidly increasing commodification of science over recent decades, the notion of a science in the public interest is still as timely as ever, as I will argue in chapter 7.

Next to these merits, however, the finalization theory has several problematic characteristics and implications. As we have seen, its authors had already confronted the problem of the definition of a closed theory, 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; 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 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 2012, 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 Houkes 2009). For instance, a fluid dynamics model of the boundary layer and the

17. See Gibbons et al. 1994. For critical reviews, see Weingart 1997 and various contributions to Nordmann, Radder, and Schiemann 2011.

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.[18] This obviously limits the value of the finalization theory for a comprehensive philosophy of technology and the technological sciences.

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 biased toward theory. It is theory formation that is seen as the core of scientific development and as the royal road to the fruitful exploitation of science for practical purposes. Since the 1980s, however, many of those writing about the philosophy of scientific experimentation have demonstrated that experimentation has a life of its own and is not limited to the testing of preexisting 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.

Lastly, 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 overly optimistic belief in social progress via 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.

EXPERIMENT AND THE SCIENCE-TECHNOLOGY RELATIONSHIP

As we have seen, the finalization approach represents a form of theory-dominant philosophy of science. 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 that John Smeaton pioneered in the eighteenth century to scrutinize and test the working and

18. On the systemic character of technology, see Hughes 1983, 1987; and Radder 1996, chap. 7. In chapters 2 and 6, I will say more about this important feature of technologies.

efficiency of waterwheels (Channell 2009) plays an important part in both experimental science and technological research. Thus, 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 (1971b, 1978) has discussed the relation between technology and the natural sciences in some detail. He conceives of these sciences as intrinsically related to technology. Like the adherents of 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 are 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 toward 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. Thus, experiment constitutes the basic link between science and technology. Following Charles Sanders Peirce, Habermas (1978, 126) explains the notion of a scientific experiment in this way: "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." 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. Later, however, Habermas changed his views on this subject, in particular by incorporating the theory-ladenness of observation and 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. Thus, it is worthwhile to take a closer look at this subject on the basis of a more detailed account of scientific experimentation.[19] The purpose of this discussion is to use 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).[20] In an experiment, we (try to) bring about a correlation between an object of study and some apparatus, and 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 produce a correlation between object and apparatus that 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.[21] 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 are neither enabling nor disturbing. For an investigator to realize a stable and reproducible experimental system, the required interactions need to be produced and maintained and the forbidden interactions need to

19. The present sketch of this account draws on analyses in my own earlier works (Radder 2012a, chap. 3; 1996, chap. 6; 2003b). Additional discussion, including a characterization of the implied notion of technology, will be provided in the next chapter.

20. For discussions and classifications of scientific apparatus, see Baird 2003; Harré 2003; and Heidelberger 2003.

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

be eliminated or prevented from taking place; the allowed interactions will cause no harm and thus do not need to be controlled.

For instance, if a particular experimental design requires a very low temperature of, say, 100°K, then we need to produce a starting temperature of 100°K and 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 implies that successful experimentation does not necessitate a completely isolated system, that is, a system that does not interact at all 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. An important part of the aim of experimentation is nevertheless 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 thus classified as "allowed." Still, it should be noted that other experimenters may contest such claims, and they might be disproved by later developments. Second, controlling the relevant interactions is, in practice, not only a matter of exercising the required material control; it also demands a degree of social discipline and control of all the people who have, or might have, an impact on the material realization of the experiment. It is these people who play, or might play, a critical role in the processes of producing or securing the required 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, any environmental impacts of an experimental system that could endanger the safety of the experimenters or other human beings are generally seen to be undesirable, and they therefore need to be prevented. Thus, the necessary control of the (required and forbidden) interactions between the object-apparatus system and its environment indicates that scientific experimentation has important theoretical, material, and social features.

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, which demands control of the relevant interactions between the technological system and its environment.[22] Again, we may distinguish between required, forbidden, and allowed interactions. Thus, in a *conceptual-theoretical sense* the successful realization of a technological system poses requirements like those needed for 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, and 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, such as a computer. Similarly, an organism that has been genetically modified in a scientific 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 thus the relevant system-environment interactions need to be controlled.

22. I do not mean to say that this is the only link between science and technology. Further similarities can be found in data processing techniques, statistical procedures, and causal analyses (see, e.g., Hacking 1992, 48–50; and Russo 2016).

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.[23] A nuclear fusion device that works well in the laboratory by no means guarantees us 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.[24] 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 in hopes of acquiring further support.

With that in mind, it is interesting to look back briefly at the finalization theory. Its proponents hold that 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 without the need for further research. The basic claim is that, in the paradigmatic stage, science policy can only promote research; it cannot substantially guide it in novel directions (Böhme, Van den Daele, and Hohlfeld 1983, 152–53). As my more detailed examination of the relations between experimental and technological science shows, however, these "scaling-up" processes are by no means straightforward. They require 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 ex-

23. 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.

24. See Radder 1996, chaps. 6 and 7, where these issues and relevant cases, such as nuclear power production, insect control, and agricultural biotechnology, are examined in detail.

pected 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 suggests two important critical questions, both of which relate to 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 necessary to guarantee the stability and reproducibility of the technological system amounts to a normatively desirable world. If one or both of these questions are answered in the negative, the only reasonable option is not to produce this particular technology. In the next chapter I return to these questions and discuss them more fully.

TECHNOSCIENCE AND 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 to each other. And indeed, philosophical studies of the science-technology relationship repeatedly advocate such a conception of science-as-technology. Examples can be found in the work of Martin Heidegger, (the early) Jürgen Habermas, Peter Janich, and Srđan Lelas. More recently, comparable views have been developed in terms of the related notion of technoscience. See the work of Donna Haraway, Bruno Latour, Don Ihde, László Ropolyi, Karl Rogers, Alfred Nordmann, and Hugh Lacey, among others. This notion of technoscience is claimed to incorporate 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 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 structure of an industrial organization.

By way of example, consider the view of Latour (1987, 131), who rejects any basic distinction between science and technology by emphasizing the constructive and adversarial nature of both: "It is now understandable why . . . 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."[25] This view exemplifies what I call the strong notion of technoscience. In this book I defend a weaker claim, saying that science and technology display, and have always displayed, many kinds of philosophically important interactions. As mentioned in the introduction, we may acknowledge this fact by metaphorically speaking about science and technology not as basically identical but as two sides of the same coin, as Kroes (2014) does. Stronger interpretations of technoscience go beyond this. First, they deny that there are any significant distinctions between science and technology, and second, they draw far-reaching philosophical conclusions from this claim. This is already noticeable in the above quotation from Latour. Similarly, Nordmann (2011) defends a strong interpretation of technoscience. He offers as the principal characteristic of the "age of technoscience" that scientific (that is, natural) objects are no longer separated from technological (that is, artifactual) objects. In the technoscientific enterprise this so-called "purification work" is claimed to be no longer possible and no longer required.

Elsewhere I have criticized such strong interpretations of technoscience in some detail.[26] I will not repeat these arguments here but confine myself to a few remarks that are relevant in the context of this book. First, the broader European notion of science, which I employ here, includes disciplines (such as historiography and philosophy) in which the intertwining with technology is far less strong, even if it is not necessarily absent. Second, most of the criticisms of the science-as-

25. Latour 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.

26. About Latour and Latourians, see Radder 1996, chaps. 5 and 8; 2004b; 2006, chap. 14. Regarding Nordmann, see Radder 2011a, 81–84.

technology interpretation presented in the remainder of this section also apply to the strong interpretation of technoscience. This pertains in particular to the technoscientific account of basic theoretical science, a subject to which I will return in chapter 7. Finally, we have seen that significant differences may obtain between the different spatiotemporal locations where science and technology are materially and socially realized. Moreover, as I will argue in more detail in chapter 2, such differences prove to be crucial in normatively evaluating scientific and technological projects.

I now turn to the science-as-technology account. As this phrase implies, science is interpreted as basically technological, as subsumed under technology. My focus is on the views of Lelas (1993, 2000), who has developed this account in philosophical detail. Lelas lays out his account in opposition 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. Whether or not theories are true is supposed to be exclusively a matter of their correspondence to a human-independent reality. Thus, when theories are true, all traces of the way we have found them, through interaction with and intervention in the world, become irrelevant and should be erased. That is to say, observation and experiment are ultimately eliminable.

From his science-as-technology perspective, Lelas (1993) 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 with and interference in nature, and he notes that scientific observation shares a number of crucial features with experiment. Through processes of experimentation and observation, which involve the making of artifacts by implementing an idea, science discovers because it invents. In Lelas's Heideggerian view, nature is at once revealed and produced. The two sides of this process—revealing and producing nature—cannot be separated, as is done in the theoria account. Lelas concludes that the productive activity of observing and experimenting, which shows their essentially technological character, 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 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, how to guide the production of experimental artefacts" (Lelas 1993, 442). Thus, the essence of scientific theories is not to be found in their abstract conceptual or mathematical structures as such but in the interpretations and translations that connect theoretical concepts or statements to the practice of observational and experimental action and production.

In his book *Science and Modernity*, Lelas (2000) develops these views about science and technology and embeds them in a comprehensive and (broadly) naturalistic 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 mammals" (100–106). In order to survive, they need to be able to adapt to a wide 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" (112).[27] 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 (177–81). Yet *modern* science, which began

27. László Ropolyi (2014, 178) advocates a similarly wide-ranging view of technology as the essential part of culture: "Human practice is of course not identical with technological practice, . . . but it always and necessarily has a technological aspect too. Moreover, every human situation can be regarded as a technological situation, every human being as a technological agent, every human goal as accomplishable by a specific technology, and every human tool as a situation-bound technological tool. The technological aspect of human practice is a response to human vulnerability and expresses the intention to gain control over the situations of our lives." See also Ropolyi's (2018) summary of his inclusive, Aristotelian philosophy of the internet.

to emerge in the sixteenth and seventeenth centuries, required two more important 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 (2000) book contains a wealth of interesting discussions, but a more detailed review is really beyond the scope of the present chapter (for such a review, see Radder 2002b). Here, I limit myself to some more specific remarks on the relationship between science and technology.

On the basis of the discussion in the previous section, 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, but only 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 experimental processes (Radder 2003b).

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, 441–42). 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 the discussion of technology as applied science, 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 that scientific theories have a meaning that transcends that of the particular experiments thus far used to test these theories. Since his 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, 88–100).

That theories have such a "surplus" meaning can also be seen by analyzing the notion of experimental reproducibility in more detail. In the previous section 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 the one that exists 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 I call 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 the two preceding sections, 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. This kind of abstraction constitutes a first step toward a wider *theoretical treatment and understanding* of the meaning and implications of this result (see Radder 2006, chaps. 8–11). 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.[28] I conclude that the meaning and function of theories cannot be reduced to their guiding function in producing specific experimental artifacts. This conclusion undermines the core of Lelas's science-as-technology view, as well as the similar views of the philosophers who advocate the strong interpretation of the notion of technoscience.[29]

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In this chapter I have addressed the relationship between science and technology, primarily from a conceptual-theoretical perspective but also with a keen eye for actual practices. As we have seen in the first section of this chapter, 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 (Mitcham and Schatzberg 2009). What results from the preceding discussion is a more differentiated account in which science and technology exhibit both similarities and dissimilarities. Starting from an intuitive preunderstanding that needs to be qualified or modified by empirical studies, we may characterize science, technology, and their relationship 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, 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 experi-

28. In chapter 5 I return to the notion of nonlocal meaning and relate it to the common good of scientific knowledge.

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

mental science, the contrast merely applies to theoretical science. Furthermore, analysis of the connections between experimentation and technology 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 epistemic, material, and social differences between science and technology. Similarly, the preceding section demonstrates that the notion of reproducibility applies to both 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.

The critical analysis of Bunge's account of technology as applied science resulted in the conclusion that this account is fundamentally flawed. The claimed epistemological subordination of technology to science and the alleged insignificance of practical craft work do not fit typical episodes of scientific and technological development. A remaining dissimilarity is a greater emphasis (in technology) on realizing external, societal objectives. Still, even this claim needs a twofold qualification. First, such objectives are, so to speak, the distal aims, which need not have an immediate impact on the proximate aims (and thus on the "outlook and motivation") of the individual technologists. Furthermore, basic science—in particular, contemporary basic science—may just as well be oriented toward such distal aims.

More generally, in agreement with the analysis by the finalization theorists, the notion of applied science has become too closely linked to views similar to those of Bunge. Therefore, to keep using this notion seems to be ill advised. Yet the fact that Bunge's view of technology as applied science is untenable does not mean that the notion of application has no point at all. And it certainly does not imply that we could do without basic (theoretical, explanatory) science, as I will argue in detail in chapter 7. For these reasons, I use the term "application-oriented science." Of course, simply replacing "applied science" with "application-oriented science" is not enough. We need to specify the latter notion 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 also experimental or observational results and techniques. What we have also seen, especially in the discussion of finalized and experimental research, is that the uses of science require "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 transfer 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 technological 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 goal of making new instrumentation may be to feed it immediately back into the development of science itself.[30] Of course, science is also often used with a view to achieving "broader societal aims." A satisfactory account of the nature and legitimacy of such aims would require much more differentiation. There is a big difference between the case of a single firm wishing to produce a specific artifact so as to enhance its profits and the case of the World Health Organization urging biomedical scientists to develop medical knowledge and technology so as to fight 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. These issues will be addressed in subsequent chapters of the book.

30. Consider 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 multipurpose research technologies, such as the ultracentrifuge, discussed in Joerges and Shinn 2001a.