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Object lessons: towards an epistemology of technoscience

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abstract

Discussions of technoscience are bringing to light that scientific journals feature very different knowledge claims. At one end of the spectrum, there is the scientific claim that a hypothesis needs to be reevaluated in light of new evidence. At the other end of the spectrum, there is the technoscientific claim that some new measure of control has been achieved in a laboratory. The latter claim has not received sufficient attention as of yet. In what sense is the achievement of control genuine knowledge in its own right; how is this knowledge acquired; and publicly validated? Notions of tacit or embodied knowledge, of knowledge by acquaintance, of engineering or thing knowledge, and reconstructions of ability or skill take us only part of the way towards answering such questions. The epistemology of technoscience needs to account for the acquisition and demonstration of a public knowledge of control that does not consist in the holding of propositions, even though it is usually communicated in writing: Technoscientific knowledge is, firstly, objective and public insofar as it is exhibited and documented. Secondly, it presupposes a specific context of technology and expertise. Thirdly, it is communicable, even where the achieved capability itself is not. Knowledge of control entails, fourthly, a knowledge of causal relationships, and it sediments itself, fifthly, as a habit of action in the sense proposed by Charles Sanders Peirce.

Keywords • Technoscience. Epistemology. Thing knowledge. Knowledge of control. Peirce.

Introduction

What counts as knowledge, how is knowledge produced, ascertained, and validated, and what is this knowledge knowledge of? These are the questions for an epistemology of technoscience and they might be summed up in the single question "What is technoscientific knowledge?" This question presupposes a contrast, since it clearly implies a distinction from the no less presumptuous question: "What is scientific knowledge?" This contrast is not intended in an historical sense, as if the technosciences and the emphasis on application-oriented research had somehow supplanted basic science only in recent years. What follows, then, is not a history of loss or decline in which, say, the scientific knowledge that springs from critical inquiry has given way to a naïve realism springing from a technoscientific focus on practical utility.[1]

Rather than venture an historical hypothesis, then, this paper contrasts two types of knowledge which may always have existed alongside one another – and certainly do so nowadays. It is not concerned with the process by which an individual researcher comes to believe this or that on the basis of some piece of evidence. Rather, this is about the kind of knowledge found, say, in a publication – in other words, the depersonalized, objective knowledge recognized (at least implicitly and over a certain period of time) by a research community. Thereby, it is also about the way in which objects appear in published knowledge claims, whether they provide evidence that confirms or disconfirms a hypothesis, or whether they are exhibited for their behaviors or properties.

On the one hand, this focus on the published knowledge of research communities makes the job more difficult insofar as epistemological theories have a harder time dealing with knowledge shared anonymously than they do with individual knowledge claims capable of being traced back to the reasons that are said to support them. On the other hand, it makes the job easier. There is no need to say anything general at all about the "technosciences" as opposed to "science". Instead, the two kinds of knowledge can be characterized as ideal types, leaving open the question of whether or not they occur in pure form, and whether or not science and the technosciences don't perhaps always intermingle with one another. Even if the methodical core of all research was essentially the same and if there were nothing distinctly technoscientific at all, the question would still remain: how are we to understand certain knowledge claims currently encountered ubiquitously in research publications, and how are we to understand the different ways in which objects gain significance?

1 It is not possible at this point to present a detailed discussion of the distinction between "science" and "technoscience". A more extensive account can be found in Nordmann (2010). As Hugh Lacey points out, most contemporary research takes place in the context of technology. Rather than distinguish between science and technoscience, we should therefore distinguish science in the context only of technology and science in the context of the environment and of society (cf. Lacey, 2012). Lacey and I therefore agree that it is the technological constitution and treatment of the objects of research rather than the interest in applicability and utility that is distinctive of technoscience. I do emphasize, however, that the philosophy of science has for the most part neglected the technological modalities of knowledge production and I therefore highlight scientific and technoscientific conceptions of objective knowledge. For this, however, no particular definition of "technoscience" is required since all that needs to be established here is the existence of these different kinds of knowledge.

1 Scientific knowledge

What kind of objective knowledge is conveyed in technoscientific research articles and is communicated in the relevant publications? In order to throw this question into sharp relief, it helps to invoke the stereotypical notion of how knowledge is presented in a scientific paper, and this notion conforms very closely to the conventions that have defined the genre of the research publication. For the characterization of scientific knowledge, then, all one needs to do is conjure in one's mind the typical scientific publication as it is imagined especially by philosophers of science. According to this stereotypical convention of the genre, the article begins with a question, a problem or a puzzle, an anomaly or a knowledge gap. One or more hypotheses are then proposed, more or less explicitly, which might answer the question or at least contribute towards an answer. After a methods section there follows a description of how new evidence has been obtained, by means of laboratory experiment or field observation, which may refute, confirm or modify the hypotheses. The article concludes with an evaluation of the hypotheses – have they been strengthened or weakened, do they require further evidence or another kind of testing, might they be revised in some manner that helps explain the evidence.[2] While the objects of research are prominent in the middle sections of the article and when concrete observations are produced, they have done their job and fade from view as soon as attention shifts back to the truth, falsity, or empirical adequacy of the hypothesis.

In this kind of scientific article, then, we are dealing with epistemic knowledge, that is, with readers being led towards a proposition which they can believe with increasing certainty.[3] In this respect, the hypothesis is literally a matter of belief, namely, a linguistic construct that becomes the object of a conviction: the conviction consists in considering the statement to be true or false, more or less plausible, or probable. Of course, one of the key features of the relationship between science and philosophy is that from its beginnings philosophy had a great deal to say about epistemic knowledge. The particular definition that has become canonical is the one according to which knowledge is true justified belief: In the realm of opinion – the *genus proximum* – those

2 It is now well known that this form of presentation does not correspond to the way knowledge is actually produced (cf. for example, Medawar, 1991; Knorr-Cetina, 1981). All that is important in the present context is that this form of presentation follows a research logic appropriate to the context of justification: if the goal of research (alleged or otherwise) is to confirm, refute or modify hypotheses, then there has to be a clear demonstration of new evidence and of its relevance for evaluating the hypotheses.

3 My use of the seemingly tautological term "epistemic knowledge" is based on Martin Carrier's distinction between "epistemic and applied science" (cf. Carrier, 2004). "Epistemic knowledge" refers to a type of knowledge that owes its existence to an epistemic interest, e.g., an interest in the achievement of theoretical understanding.

opinions qualify as knowledge that satisfy as *differentia specifica* the joint-condition of being true and being justified through the provision of reasons. The limits to this definition have been discussed in detail, at least since it was shown that it provides at best necessary but not sufficient conditions (cf. Gettier, 1963; Moser, 1996). In respect to the objective scientific knowledge presented in a scientific journal, this definition is limited additionally by the fact that in the publication there is no place for the subject to express a belief, be it the belief of the text's author or be it the belief of the scientific community as a whole (assuming that communities can hold beliefs). Instead, the scientific article merely offers up to its readers the opportunity to revise their beliefs. It does so by bolstering or weakening them in that it shows how the evidence presented here more or less clearly confirms or else runs counter to a particular hypothesis. This might then contribute to the emergence of intersubjective agreement about the relative merits of a hypothesis as a proxy to shared belief.

Instead of expressing a belief, the scientific publication contributes to the process of communal belief formation.[4] It is thus part of a public process of justification which, in principle, is always incomplete and which refers to shared methodical standards and aims at the achievement of true belief as the end of inquiry.[5] There is no means to ascertain the truth of the belief independently of this justificatory process – no way to check against some facts once and for all. This is why sociologist of science Robert Merton chose to speak of science as the pursuit of "publicly certified knowledge" (cf. Merton, 1973, p. 270; Ziman, 1968).

Given that the pursuit of scientific knowledge aims for better justified beliefs that, in the long term, approximate or converge upon the truth, the general role of scientific publications for the evaluation of hypotheses is quite clear. The momentary or initial appearance that a hypothesis accords with reality is never enough; it always requires systematic demonstration, empirical evidence, and theoretical explanation, from which emerge sound reasons for accepting it. While the observation or experimental manipulation of objects are at the focus of many publications, they neverthe-

4 To be sure, one might argue that scientific journal article present the true justified belief that some observed fact stands in a particular evidentiary relation to a hypothesis. Sure enough, but this appears to be logical rather than empirical knowledge (assuming that logic is a matter of opinion, belief, knowledge), and it is not the knowledge the achievement of which is intended in the process of inquiry.

5 I deliberately leave aside all attempts to establish the degree of belief of the scientific community as a whole. My rough and ready characterization of the open-ended process of justification may sound Popperian but is thoroughly compatible with a Bayesian approach according to which the evidence published in a journal modifies the degree of belief of its readers: Although different readers bring different assessments of the hypothesis to bear ("prior probabilities") and although the revision of their judgment leads to correspondingly different degrees of belief ("posterior probabilities"), the introduction of new evidence contributes to a process of gradual assimilation of the individual degrees of belief.

less play a fleeting role in the public procedures of testing a hypothesis that serve to strengthen or weaken belief in that hypothesis. What is observed is some behavior of the object and this observation serves an inferential purpose and is only one of an indefinite number of observations that culminate in tentative and final determinations of truth, falsity, or probability.

The conventions that define the genre of the scientific article thus correspond to a canonical conception in the philosophy of science. Scientific knowledge is completely bound to processes of public justification, and the fixation of belief can only emerge from these processes in the context of an ever-ongoing process of enlightenment that subsumes all particulars and that generates universality by leaving individual things behind.

2 Epistemic knowledge and thing knowledge

In order to substantiate the claim that technoscientific journal articles present a completely different kind of knowledge and a different kind of object, one should be on the lookout for an alternative epistemology that might account for this difference. Here it is tempting to take a cue from the term "technoscience" and its reference to "technology" or "technique", evoking an epistemology of ability or skill, of implicit or personal knowledge embodied, say, in the practice of a craft, since this is knowledge of the "I know how to ride a bike"- variety, however, it is not what we are looking for (cf. Mildenberger, 2006). Here we are concerned, after all, with objective knowledge as it is presented and made available in a scientific publication. Accordingly, Davis Baird's theory of "thing knowledge" may be a far more likely candidate for characterizing this type of knowledge (cf. Baird, 2004). By contrasting Baird's thing knowledge with epistemic knowledge it can be shown that it does, indeed, point in roughly the right direction, but that it still doesn't adequately characterize technoscientific knowledge.

Baird's conception of thing knowledge has its origins in the comment made by Ian Hacking that scientists analyze the complexity of the real world in two fundamentally different ways.

> We do so by distinguishing, in the mind, numerous different laws. We also do so, presenting, in the laboratory, pure, isolated phenomena (Hacking, 1983, p. 226).

Now Baird regards the experimental presentation of phenomena, mentioned second by Hacking, as also being a kind of knowledge production. A first strand of the argument in support of this view does not support the distinction between scientific and technoscientific knowledge but exposes, instead, that Hacking and Baird for the most part embrace a rather traditional image of science. What both criticize is a view that equates science with theory. In contrast, they plead that scientists provide representations of reality not only through theory but also through the creation of symbolic as well as material models as well as through phenomena. It is because phenomena are rare and because they represent the lawfulness of nature that scientists are mastering complexity by creating and stabilizing phenomena.[6] However, what remains unquestioned and intact on this view is the notion that science is in the business primarily of representation – with no provisions as yet for a production of knowledge and a control of objects that is not representational.

There is a second strand, however, in Hacking's and Baird's argument for the relative autonomy of experimentation and the creation of phenomena vis-à-vis the development of theory. According to this strand of argument, we explore the stock of phenomena through experimental or technical practice and thereby find out how things behave and what it takes to reproduce them reliably. Unlike scientific knowledge, with its complicated relationship between current public processes of justification and a belief that becomes established somewhere down the road, thing knowledge provides its own justification directly and immediately: in Hacking's words, it is "self-vindicating". The technologically implemented mastery of phenomena proves itself through the reliability and reproducibility of its own generation, and knowledge of a phenomenon coincides with the latter's material production or presentation. The technical mastery of the phenomenon validates itself, which is why it would be quite inappropriate to speak here of truth and falsehood. Statements and other representations that say something about the world can be true or false. The working of a machine is not true or false – the machine either works or it doesn't work. To take one of Baird's examples, electrical circuits are articulated similarly to linguistic statements, except that they don't need to correspond to a world represented by them because they institutionalize a reliably efficacious system of interdependent material things which more or less speaks for itself (cf. Baird, 2004, p. 8 ff.).

This gives rise to an ineluctable but benign circularity of thing knowledge. Thing knowledge is expressed in the reliable functioning of a machine; at the same time, the fact that the machine works is proof of the existence of thing knowledge. Although this circularity also holds for any actually given belief of an individual, it does not hold for the epistemic knowledge that is to be acquired by the scientific research process. The belief of some individual is expressed in a corresponding disposition of that person to act accordingly; at the same time, someone's true or even false belief becomes manifest

6 Consider especially "the break" that is inserted between the two main parts of Hacking (1983). Here, the case is made emphatically that intervention, too, is the work of *homo depictor* and not of *homo faber*.

when he or she reveals the corresponding disposition to act: The behavior is the criterion for the existence of the belief that is said to be expressed by the behavior. By contrast, the epistemic knowledge pursued by science maintains a critical distance to mere belief, if only because any actually held belief might fail to be true or justified as yet.

Baird's conception of thing knowledge develops one side of Hacking's distinction between two scientific activities, namely the stabilization of phenomena. Accordingly, Baird's concern is to elucidate the latter and to characterize scientific thing knowledge. Baird's account suffers, however, from the subsequent impossibility to distinguish scientific from non-scientific thing knowledge. The mastery of phenomena achieved by a researcher in the laboratory, by a product developer, by a worker at a machine, or by an ordinary user of technical devices ultimately amounts to the same thing, namely, the capacity to exploit the reliably efficacious system of interdependent material things. When Baird speaks of "scientific" thing knowledge, all he means is that thing knowledge has some attributes that are also characteristic of epistemic knowledge in the sciences, e.g., that it represents something. In particular, according to Baird thing knowledge like propositional knowledge is objective, public and communicable, indeed, the very development of thing knowledge is one of science's major achievements (cf. Baird, 2004, p. 127 ff.). Baird sees in Karl Popper's world 3 of objective knowledge not only statements that can be published in the form of hypotheses and presented for discussion to the scientific community; rather, it also contains material constructions which we can show to each other, which can be passed from hand to hand, taken apart and put back together again, in order to find out how they work and, if necessary, to modify them (cf. Baird, 2004, p. 15 ff., 115 ff.; Popper, 1979). Thus, according to Baird, scientific progress can happen also at the level of the pure, non-linguistic, unspoken mastery of phenomena.

The contrast between epistemic knowledge and thing knowledge can be pinpointed by focusing on the form of their respective knowledge claims. An epistemic knowledge claim selects the written form of a publication. Here we have a question or a hypothesis, and for those who understand the technical language, its meaning is contained entirely in its formulation. This meaning consists in the fact that on the basis, for example, of its truth conditions, the hypothesis prompts a public process of justification. And over here we have experimental evidence obtained through calculation and observation, which serves to evaluate the hypothesis or leads to its modification. The expected growth of knowledge comes from the linguistic content of the hypothesis along with the evidence presented – together they advance public certification and, in the long run, the establishment of true belief. The claims of thing knowledge, by contrast, are embodied in a machine or an experimental setup: here I am, look at me, take me apart and put me back together again, tinker with me in a creative way, vary my components, get a feel for the way I work, and get to know the way my mechanism connects inputs and outputs with one another. The reliability claimed by thing knowledge, and the stabilization of certain phenomena associated with it, is contained in the things themselves.

Contrasting these two ways of achieving knowledge shows nice and clearly that not every kind of knowledge generated in research laboratories is epistemic knowledge. However, it does not suffice to capture what is here called technoscientific knowledge. Baird's thing knowledge is so emphatically opposed to everything propositional that the most it would correspond to on printed paper would be a construction manual, a technical drawing, or a description of a machine that exists somewhere. However, technoscientific knowledge encompasses the research findings from materials science, nanotechnology and biotechnology and everything that is published as so-called application-oriented basic research – including, of course, research results from synthetic chemistry and the engineering sciences. This is public, communicable, objective and objectified knowledge that does not consist solely in the working or not working of a material apparatus.

3 Technoscientific knowledge

A technoscientific research article does not begin with the statement of a theoretical problem and a hypothesis. The following, for example, is the beginning of a "Letter to *Nature*" from 2004, a text in the journal *Nature* whose designation as "letter" plays on the classical format of a research report that goes back at least to the early days of the *Transactions of the Royal Society*.

> Nanoelectromechanical systems (NEMS) hold promise for a number of scientific and technological applications. In particular, NEMS oscillators have been proposed for use in ultra-sensitive mass detection, radio-frequency signal processing, and as a model system for exploring quantum phenomena in macroscopic systems. Perhaps the ultimate material for these applications is a carbon nanotube. They are the stiffest material known, have low density, ultra-small cross-sections and can be defect-free. Equally important, a nanotube can act as a transistor and thus may be able to sense its own motion. In spite of this great promise, a room-temperature, self-detecting nanotube oscillator has not been realized, although some progress has been made. Here we report the electrical actuation and detection of the guitar-string-like oscillation modes of doubly clamped nanotube oscillators. We show that the resonance frequency can be widely

> tuned and that the devices can be used to transduce very small forces (Sazonova *et al*., 2004, p. 284).

The text begins with the challenge of meeting certain expectations concerning all that is thought to be possible in the brave new world of nanotechnology. On their journey, the researchers enter this space of possibilities and select the materials and experimental procedures suitable for producing something they themselves and then the editors of *Nature* in particular describe as a guitar (cf. Cleland, 2004): A carbon nanotube is stretched out like a guitar string, set vibrating, and can even be tuned. This text does not say "here is a hypothesis, and here is the evidence to confirm or refute it", and neither does it say, "here is an apparatus, look how it works". Instead, it says, "here is a sign or proof of what we are capable of doing in our laboratory". In this case, a nano-guitar has been built; sometimes something is done at room temperature which others can do only under extreme conditions, and sometimes something is measured more precisely or modeled more effectively than had previously been possible. In all cases, an object is shown to work like a novel device even where it is by no means an accomplished technical artifact. Accordingly, the text goes on to recount how the more or less amazing deed has been done. Without teaching the readers how to reproduce what is described, it offers enough hints to at least challenge them to acquire the capability described themselves and even to develop it further. Often, but by no means always, it is then demonstrated that the amazing phenomenon is compatible with existing epistemic knowledge, in other words, that it can be modeled or simulated by available means; this is sometimes considered an "explanation" of the phenomenon. The text finishes roughly the way it began: "The combination of high sensitivity, tunability, and high-frequency operation make nanotube oscillators promising for a variety of scientific and technological applications" (Sazonova *et al*., 2004, p. 287). Here, the scientific achievement is not contained in the significance of the hypothesis, nor does it consist in the functioning of an apparatus. Instead, it consists in a demonstration of the promising capability that has been acquired, that is, in a credible report or a data set or film stored on the *Nature* website.

Technoscientific knowledge consists in the acquisition and demonstration of basic capabilities. These capabilities are basic because they do not involve the design and development of devices or even products (one significant exception to this are scientific instruments). This holds at least for university-based technoscientific research and despite all the promises of technological innovation and the not inconsiderable pressure to generate practical applications. Rather than being applied science or applied technoscience, then, there is basic technoscientific research which consists in demonstrated capabilities to visualize, to characterize substances, to measure and model – and, of course, to manipulate and control surprising phenomena. One highly regarded capability in bio- and nano-technical research, for example, consists in positioning carbon nanotubes in specific places and allowing them to grow in a controlled manner or writing the name of one's laboratory and using a completely new technique for doing so (cf. Nordmann, 2006). And on the voyages of discovery that are undertaken in newly opened spaces of possibility for future technologies, surprising properties are continually explored as to whether they afford still further technological capabilities – to discover, for example, whether the resonance of a nano-guitar can be functionalized to serve as a sensor.

In line with the disclaimer at the beginning of this piece, it does not matter for the purposes of the present argument how typical such research publications are that do not focus on the truth or falsehood of statements but seek to demonstrate an acquired capability. Those interested in the rise of the technosciences and the fall of science might like to count the relative frequency of each different publication format. I am not alone in believing that stories about acquired capabilities ("I made a nano-widget") are becoming predominant in many prominent fields of research (cf. Jones, 2011). Yet even if this was only a niche phenomenon in the research landscape, the question still arises as to the kind of knowledge being presented and communicated in these texts.

I approach this task by picking a somewhat more complex example of technoscientific story-telling. It allows me to take a closer look at the relationship between epistemic theoretical knowledge and technoscientific capability or knowledge of control. The text in question is one that was published in 2004 in the journal *Nanotechnology*. Its subject matter is temperature-dependent effects in the transition from an electrode made of gold to a wire consisting of an organic molecule. The first three sentences of this text bring into play rather different ideas which appear to oscillate between epistemic knowledge claims and knowledge of control, but which become completely drawn into the technoscientific idiom.

> The recent surge of activity in molecular electronics is driven by expectations of scientific inroads into the realm of the molecular state and by the anticipation of a high technological payoff. Continued progress in this area depends critically on developing a thorough understanding of the fundamental processes of charge conduction through individual or small assemblies of molecules connected between two reservoirs of charge carriers, usually metallic leads. This understanding relies on concepts and theoretical methodologies that have been developed and applied to study molecular charge transfer in donor-bridge-acceptor systems (Selzer *et al*., 2004, p. 483).

The obligatory reference to technological potential is followed here, first, by the call for a "thorough understanding" of certain processes. The authors then emphasize that this understanding is based on previously developed concepts and theoretical methods. Now, does this mean that the acquisition of technoscientific knowledge of control can exist only in the context of continued acquisition of epistemic knowledge and that it does not constitute a separate research program of its own? This might appear to be the case at first glance, but as it turns out, notions like "understanding" or "explanation" take on a different meaning as they move from one context of knowledge-production to another.

To the extent that knowledge here consists in the capability to interact with some object, the "thorough understanding of a fundamental process" is firmly within the sphere of capability and control and does not assume the character of theoretical knowledge. This is not to deny, of course, that epistemic knowledge plays a considerable role: as a stock of knowledge and methods it enters into the acquisition and fortification of capabilities. Its role is therefore quite unlike a Kuhnian paradigm, which provides the necessary preconditions for identifying and solving problems and which in the course of problem-solving is developed or articulated further. In the technoscientific context, instead, the knowledge acquired over the course of the last three hundred years serves as a toolbox containing very heterogeneous and incommensurable concepts, representational techniques, algorithms and models that can be drawn upon opportunistically in order to represent, simulate, or explain phenomena and processes (cf. Nordmann, 2008). When a simulation model is thus constructed from selected bits of available theory, this is only another acquired capability of intellectual, e.g., predictive control. A phenomenon is thought to be explained when one can present it not only in the laboratory but also in a model (cf. Wise, 2004). In other words, accumulated epistemic knowledge feeds into the acquisition of capabilities but does not emerge from it. This becomes evident when, later in their account, the researchers indicate how they actually pursue their search for thorough understanding.

> Recently, we began to investigate the role of thermally activated conduction in conjugated molecules that span a gold electrode gap. We observed a temperature-induced transition between coherent tunneling and thermally activated incoherent hopping conduction in single molecule junctions, which is in good agreement with theoretical predictions. Here, we extend the analysis of these two transport mechanisms as they pertain to our experimental system, and present experimental data that suggests local heating due to dissipation in the molecule might also contribute to the transition from one to the other. More specifically, these data suggest that it is the vibrational temperature of the molecule rather

> than the temperature of the overall system (i.e., bath temperature) that determines the dominant conduction mechanism (Selzer *et al.*, 2004, p. 484).

First, the researchers establish that the cause of a temperature-induced transition between two modes of electron transport is indeed temperature. They establish this neither in the mode of hypothesis-testing, causal analysis, or inference to the best explanation, nor by establishing an anomaly that awaits resolution. Instead, they point out that this way of inducing the transition is "in good agreement with theoretical predictions" that are constructed in a simulation model. Contrary to the received notion of a theoretically predicted numerical value that is prior to the event and that is expected to agree with a measured value, good agreement here consists in the successful construction out of theoretical building blocks, after the fact, of a model system that looks like the observed experimental system. In other words, two capabilities come together here which mutually validate one another – the capability of the experimenters and the capability of the modelers. This confluence is implicitly taken to be explanatory and it allows for further differentiation between the overall temperature of the system and the vibrational temperature of particular molecules which are not independent of one another and which can therefore be differentiated only relative to capabilities of accessing vibrational temperatures in the system.

So, in which sense other than assimilation to technical capability has a "thorough understanding of a fundamental process" been achieved? Fundamental mechanisms are identified by showing their structural correlation to technical action and, if available, its reproduction in a simulation model. This is reiterated in the summary and conclusion of the paper:

> The effect of temperature on conduction through a molecular junction (…) has been studied. Qualitative and semi-quantitative agreement with theory has been observed. Open issues regarding the observed activation energy of the thermal conduction process, as well as the difference between the effective temperatures of the junction and of the surrounding system have been discussed. These results further suggest that the exact temperature dependent conduction behavior of a given molecular junction will depend critically on the specific molecular structure, in particular the rotational barriers between adjacent rings and conduction units. Such structural correlation studies are now underway in our laboratories and should elucidate further important details of the fundamental conduction mechanisms (Selzer *et al.*, 2004, p. 287 ff.).

In light of this approach, the notion that fundamental mechanisms will be shown to depend upon specific molecular structures does not involve the expectation that more powerful and general laws will be found at deeper levels of organization. Instead, greater technical detail is expected to show that many things happen at this level of detail – in the end, everything depends on the specifics of the situation. Technoscience develops the capabilities to access and perhaps control the specifics to some considerable extent even though it may well turn out that there are as many of these mechanisms as there are molecules. Thus "thorough understanding" consists in the capability to identify, model, and control these mechanisms in each specific case – it yields rules of thumb, at best, but not the formulation and validation of descriptive theories.

The article in question does not produce epistemic knowledge and does not establish a justified true belief, nor does it present thing knowledge and the self-vindicating reliable functioning of a device or machine. The interaction between the researchers and their experimental system – in this case, a molecular junction – does not "ascend" beyond that system to theories or laws, not does it transform this system into a practical working device, e.g., by insulating, encapsulating, functionalizing it. Instead, the exploration of the molecular junction appears to empower simultaneously the researchers (who acquire a new capability of control) and the individual molecules (for which their vibrational temperature is ascertained to be causally relevant above and beyond the temperature of the total system).[7]

4 Public Demonstrations

If technoscientific knowledge of control of phenomena is distinct from scientific knowledge and manual dexterity in equal measure, this middle ground needs to be staked out more carefully for a theory of technoscientific knowledge. If the identification of true justified beliefs can draw for its examples on scientists but also on decision makers in everyday life, if the epistemology of implicit or personally embodied skills can look to bicycle riders and artisans, and if the notion of thing knowledge is exemplified by engineers and tinkerers, what are the models for technoscientific knowledge and its public demonstration of the achieved acquisition of basic capabilities? In the following I suggest that the recording of a piece of music might serve as a model or analogue here and that a theory of technoscientific knowledge can learn from the in-

7 The simultaneous accrual of power or habit and the simultaneous achievement of new competences can be found in the accounts of Peirce and Latour (cf. Nordmann, 2009).

teraction of pianists with their objects of knowledge that include a written score, a musical instrument, a technical recording medium, a composer, and an audience.[8]

Whatever might be said of the builders of the nano-guitar can also be applied to a recording, for example, by pianist Alfred Brendel, who in this way furnishes testimony to his way of playing a Schubert sonata. Not only does he thereby demonstrate artistry and capability, but he also opens up a new view and establishes a new phenomenon, one which is objectively given, communicable and teachable, and which gives rise to patterns of expectation for listening and performing. Five characteristics stand out if one considers technoscientific knowledge of control alongside Brendel's demonstration of capability as an achievement of knowledge. A cursory survey of these characteristics is as far as I can go at this point to prepare the ground for a theory of technoscientific knowledge.

Technoscientific knowledge is, firstly, objective and public insofar as it is exhibited and documented. Secondly, it is not like thing knowledge, which is general and thus available to lay people as well, but instead it presupposes a specific technological and cultural context. Thirdly, technoscientific knowledge is communicable, even though the capability itself is not. Knowledge of control entails, fourthly, a knowledge of causal relationships, and it sediments itself, fifthly, as a habit of action in the sense proposed by Charles Sanders Peirce. These five characteristics should not be mistaken for criteria that need to be met by technoscientific knowledge claims and against which they will be measured. If they were criteria, they would be satisfied just as soon as the knowledge claim is advanced and as soon as a capability has been acquire. Before technoscientific knowledge is acquired, there is no claim to be made, and once it is acquired the capability can also be demonstrated – as opposed to the claim that some scientific hypothesis might be true which can be made well in advance of any provisions of evidence.

First, then, knowledge of control is objective and public. However, it is not published in the form of, say, recipes – that is, not as a conglomeration of theories, methods and conclusions, where its objectivity would derive from its verifiability, reproducibility and agreement with pre-given instructions. It is not procedural rigor that accounts for the objectivity of the nano-guitar, nor does Brendel's objective achievement consist in the fact that he more or less faithfully follows a score. Likewise, the objectivity of technoscientific knowledge does not reside in the form of manufactured

8 It is provocative, of course, to compare technoscientific research to the work of a recording artist – but the provocation does not consist in the claim that the two activities are basically the same. The provocation is that we lack an epistemological account for both activities. In the course of developing such an account, one will move beyond the superficial analogies also to the significant differences between both cases.

artifacts, for example, in the form of electric circuitry inside a material object, of the experimental setup in a laboratory, or of a record or CD that features Brendel's recording. Instead, a sign or demonstration of success is made public. In contrast to purely individual and merely subjective achievements, objective knowledge of control is based on its publication in journals. As such, it involves a collective judgment that the claimed achievement is plausible and fits into an international matrix of established capabilities that are already distributed among the relevant laboratories. This is also what defines the objective achievement of the pianist Brendel. His novel interpretation of Schubert's score makes sense to his community of musical experts, it fits in with other ways of playing Schubert but expands ever so slightly what is already familiar and known.

Second, knowledge of control requires participation in an epistemic culture that shares in a stock of accumulated knowledge and research technologies. Though the acquired capabilities are rooted in this culture, their acquisition does not serve to methodically expand the stock of knowledge, and only incidentally or in special cases does it serve to improve the instruments of research. Technoscientific knowledge of control is parasitic upon a surplus of available scientific knowledge and instrumental technique that has been accumulated over the past several hundred years. These feed into the acquisition of capabilities by way of experimental and arithmetic procedures, recognized regularities, causal relationships, and proven algorithms: these can be drawn upon opportunistically for purposes of theoretical modeling and thus "explanation". Similarly, Alfred Brendel's knowledge of control and his commanding performance of the Schubert sonata depend on musicological knowledge and specific technical conditions, though he does not contribute to musicological knowledge with his playing of the sonata and does not test any assumptions about the acoustic properties of a piano. In a sense, the beliefs that enable knowledge of control play no role at all but fade into the background just as soon as they enter into its acquisition – they are not confirmed by it and are not thematized at all. They are background knowledge, quite literally, and not themselves discussed, problematized, criticized or improved upon through the acquisition and demonstration of a basic capability.

Knowledge of control is, third, communicable, though not in the form of some content that can be expressed in propositional form and that is immediately accessible by all members of a linguistic community simply by virtue of grasping the meaning of sentences. Also, unlike thing knowledge achieved capabilities are not communicated by being passed on from laboratory to laboratory in the form of a device or codified procedure. And neither is it tacit or implicit knowledge that becomes embodied in the course of an apprenticeship or in the course of being socialized through shared practices; the acquired capabilities referred to here are essentially new and create new foundations for action and behavior. Finally, the knowledge of controlling certain phenomena and practices is not communicated or taught by being narrated and made public in some way, as little as Alfred Brendel's recording can teach us how to play the piano or how to understand a Schubert sonata. What is communicated is not the knowledge of control or the acquired capability itself but only the fact that it has been acquired and demonstrated by somebody. This communication is meaningful only if we presuppose the existence of an institutional structure which enables those who have only heard of its existence to acquire the capability or a variant thereof through independent reconstructions of the steps that are likely to be necessary. Laboratory architectures and experimental cultures are examples of such an institutional structure, as are orchestras and music academies.

Fourth, knowledge of control involves an intimate and, so to speak, atheoretical knowledge of causal relationships. System properties are articulated physically such that their dependence upon one another can be felt – just as simulation models convey a feeling of a quasi-organismic dynamic, or of parameter dependencies and system boundaries (cf. Lenhard, 2006, p. 163). Systematic parameter variations allows for the practical identification of so-called INUS conditions, that is those conditions that are "Insufficient but Non-redundant parts of a condition which is itself Unnecessary but Sufficient" for the occurrence of a physical effect or behavioral response (cf. Mackie, 1974). As opposed to the other characteristics of technoscientific knowledge, this one suggests a continuity between scientific and technoscientific approaches, especially as it directs our attention towards the technical, or practical, aspect of epistemic knowledge production as well. With regard to implicit and explicit procedures of causal analysis, the difference between science and technoscience might appear to consist only in their respective objectives: epistemically oriented knowledge is concerned with a proper understanding and systematization of causal relations, whereas knowledge of control of causal relations supports capabilities of measurement, visualization, modeling or mastery of phenomena (cf., e.g., Carrier, 2004). This continuity between scientific and technoscientific knowledge claims is only apparent, however, as can be seen in the example, once again, of the pianist. Brendel's acquired capability involves an intimate, experiential, and experimental knowledge of creating aesthetic effects and of controlling, so to speak, the emotional response of his listeners. Even as Brendel deliberately produces certain effects, however, this is a far cry and radically discontinuous from the endeavors of a neuropsychology of perception that seeks to understand what is causally responsible for the generation of aesthetic effects.

Finally, knowledge of control becomes sedimented as a habit of action in the sense of Peirce (1992). Just as the technosciences follow upon the sciences not by applying theories but by taking up as tools the many theories and techniques that have accumulated over time, so the Peircean habits of action emerge as intellectual activity disappears. For Peirce, habits signify the achievement of knowledge that does not need to be questioned, that has nothing theoretical or hypothetical about it anymore.[9] A habit of action, achieved capability, or knowledge of control guides us even in complex situations when we can safely rely on intersubjectively available causal relations and when we are cognizant immediately of this reliability and robustness rather than merely interpreting it as grounded in and derived from general laws. The collective, reliable, publicly exhibited and intersubjectively accessible assimilation and control of how a system behaves signifies quite simply that we are able to find our way about in it. And knowing our way about is tantamount to the achievement of adapting to the circumstances of a specific, highly complex world – just as Alfred Brendel knows his way about Schubert's score and as technoscientific researchers learn to move about in the nanoworld that has been opened up to them by scanning probe microscopy. The epistemic knowledge of the classical disciplinary sciences feeds into this elementary mastery of phenomena or systems and disappears in the formation of habits that are grounded in intimate familiarity with the behavior of a system or complex set of relationships. The justified beliefs or bodies of knowledge of classical physics and quantum chemistry and of hydrodynamics and complexity theory no longer appear at all to be theoretical propositions or beliefs; rather, they tacitly inform technoscientific action. In their ontological indifference and without much effort at reflecting on their methods or concepts, the technosciences can cheerfully go about their main business, namely that of building themselves a brave new world.[10]

Conclusion

We encountered numerous types of knowledge claims in the preceding analysis and comparison of "scientific" and "technoscientific" knowledge. There was firstly, of course, the ordinary case where a belief qualifies as knowledge if it is true and properly justified – this holds for claims as to what time it, whether there is milk in the refrigerator, or the like.

The finding of a classical scientific research publication also qualifies as knowledge if it is true and justified. That finding, however, is only a small contribution to an overarching process of justification of the truth or falsity of some hypothesis or theory under consideration. The belief may well be true and justified that evidence has been

9 This is not to say that expectations cannot be frustrated; but when a technical expectation clashes with reality this is not the same as when a hypothesis fails to be confirmed in a test (cf. Nordmann, 2009).
10 Regarding the notion of "ontological indifference", cf. Galison (2006); Daston & Galison (2007), p. 393, 414.

discovered which supports or fails to support a hypothesis. In and of itself, however, the report of the availability of evidence is not interesting or important. What one wants to know, after all, is whether the hypothesis is true or false.[11] But, thirdly, the belief in a scientific hypothesis never quite qualifies as knowledge – partly for the well-known Popperian consideration that its truth cannot be ascertained independently of a process of justification which never comes to an end. Belief in a hypothesis does not qualify as knowledge also because the scientific community rarely cumulates the beliefs of individual scientists, no matter how justified they might be on Bayesian grounds. An individual scientist may well believe a hypothesis to be true because the process of justification has produced evidence as forceful and persuasive as one can reasonably expect. But this belief never enters into the formation of a belief of and by the scientific community as a whole.

Just like knowledge of an evidentiary relation, the report of an achieved capability also qualifies as knowledge if it is true and justified. Upon reading a peer-reviewed publication the reader can know that researchers in some laboratory have the capability to grow carbon nano-tubes in a controlled manner. Though for a different reason than above, this type of knowledge is also not particularly important and interesting as far as knowledge production is concerned. It is uninteresting because the scientific community does not normally call into question reports of what some scientists have actually done. These kinds of reports are only the starting point for the larger purposes of scientific and technoscientific knowledge production.[12] The acquired capability qualifies as a fifth type of knowledge of how to control phenomena and processes if it can be demonstrated publicly – and the writing of a report about this is only a (common but unnecessary) part of the process of demonstrating that one can actually visualize, manipulate or model something. This knowledge claim qualifies as knowledge just in virtue of being made – it is self-vindicating and requires no drawn-out, let alone unending process of justification.

Beyond these five kinds of knowledge, we encountered a variety of claims that are variants of "thing knowledge" and that belong in the realm of technology and engineering rather than science or technoscience. In contrast to knowledge of control that is established by way of technoscientific research, these include the knowledge of han-

11 See note 4 above. To be sure, true justified belief of an evidentiary relation should be counted as a knowledge claim in its own right.

12 Of course, such claims can be impeached, too – one can mistake an experimental artifact for an achievement of control, and some scientists have deceived others about their achievements. But this does not touch upon the categorical distinction between scientific and technoscientific knowledge claims – only scientific knowledge claims of the third type lead into an unending quest for definitive knowledge.

dling and use, the knowledge of making, building, repairing, and the knowledge of design. And whereas the claim of having achieved a capability of control consists in a publicly certified report that this achievement can be and has been demonstrated, the variants of thing knowledge are established by way of artifactual demonstrations. Here it is not only some report but the structures, devices, artifacts themselves that embody intersubjectively accessible evidence of achieved making, building, or design: engineers managed to build this dome, or the circuitry on a chip relates inputs to outputs causally and formally.

This great variety of knowledge claims shows compellingly, that one cannot understand research practice by considering knowledge as a species of opinion only. The present paper emphasized this. It contrasted especially the third and fifth type of knowledge in that the former is characteristic, even defining of scientific knowledge-production, and the latter of technoscientific knowledge. If the former claim leads into an unending process of justification, this is because it takes the form of a proposition about the nature or the properties of some object of interest. It considers objects as nodes in a network of relations that make up the real physical world of mind-independent phenomena. Such claim could only qualify as knowledge, then, if it would be possible to ascertain that the object really and always has this nature or these properties, and that, accordingly, it really does stand in this or that nexus of lawful relations. In contrast to this unbounded task, the claim that a research group can grow carbon nano-tubes in a controlled fashion is just between the object, the researcher, and the expectant public, and it is validated by the demonstration of the object's behavior. The object does not signify a nexus of lawful natural relations but only what it presently affords in the context of manipulation.

Epistemology and philosophy of science have a lot to say about knowledge as a species of opinion – do we have good reasons to accept it as a true belief, can we ascertain the agreement between our theory and reality? But epistemology and philosophy of science have hardly anything to say as yet about technoscientific knowledge – not only how it is established and validated but also whether it can be judged as better or worse, more and less robust? As in the case of the recording of a Schubert sonata, how can we distinguish true virtuosity from bland repetition? And do we look at the researchers to determine this, at their objects, or at the different ways of beholding things and interacting with objects of research? We are only beginning to address these questions by attending to research practice as a technological pursuit to achieve and demonstrate control in a world of surprises.

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