1 Instrument Epistemology

> If your knowledge of fire has been turned
> to certainty by words alone,
> then seek to be cooked by the fire itself.
> Don't abide in borrowed certainty.
> There is no real certainty until you burn;
> if you wish for this, sit down in the fire.
>
> JALAL AL-DIN RUMI,
> *Daylight: A Daybook of Spiritual Guidance*

Knowledge has been understood to be an affair of the mind. To know is to think, and in particular, to think thoughts expressible in words. Nonverbal creations—from diagrams to densitometers—are excluded as merely "instrumental"; they are pragmatic crutches that help thinking—in the form of theory construction and interpretation. In this book I urge a different view. I argue for a materialist conception of knowledge. Along with theories, the material products of science and technology constitute knowledge. I focus on scientific instruments, such as cyclotrons and spectrometers, but I would also include recombinant DNA enzymes, "wonder" drugs and robots, among other things, as other material products of science and technology that constitute our knowledge. These material products are constitutive of scientific knowledge in a manner different from theory, and not simply "instrumental to" theory. An example will help fix my meaning.

1. MICHAEL FARADAY'S FIRST ELECTRIC MOTOR

On September 3 and 4, 1821, Michael Faraday, then aged thirty, performed a series of experiments that ultimately produced what were called "electromagnetic rotations." Faraday showed how an appropriately organized combination of electric and magnetic elements would produce rotary motion. He invented the first electromagnetic motor.

Faraday's work resulted in several "products." He published several papers describing his discovery (1821b; 1821a; 1822c; 1822d). He wrote letters to many scientific colleagues (1971, pp. 122–39). He built, or had built, several copies of an apparatus that, requiring no experimental knowledge or dexterity on the part of its user, would display the notable rotations, and he shipped these to his scientific colleagues (1822b; 1822a; 1971, pp. 128–29).

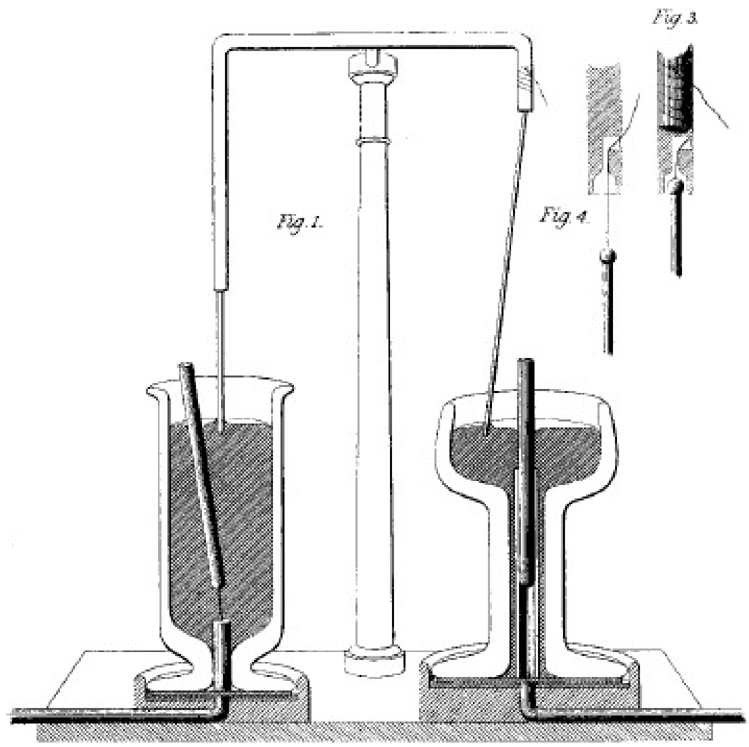

FIGURE 1.1 Michael Faraday's 1821 electric motor (from Faraday 1844).

A permanent magnet is cemented vertically in the center of a mercury bath. A wire, with one end immersed a little into the mercury, is suspended over the magnet in such a way as to allow for free motion around the magnet. The suspension of the wire is such that contact can be made with it and one pole of a battery. The other pole of the battery is connected to the magnet that carries the current to the mercury bath, and thence to the other end of the wire, completing the circuit (see fig. 1.1).

The apparatus produces a striking phenomenon: when an electric current is run through the wire, via the magnet and the mercury bath, the wire spins around the magnet. The observed behavior of Faraday's apparatus requires no interpretation. While there was considerable disagreement over the explanation for this phenomenon, no one contested what the apparatus did: it exhibited (still does) rotary motion as a consequence of a suitable combination of electric and magnetic elements.

2. DEVICE EPISTEMOLOGY

How should we understand Faraday's device? One could say that it justifies assertions such as, "A current-carrying wire will rotate around a magnet in a mercury bath as shown in figure 1.1." One could say, and Faraday did say, that the phenomenon exhibited by the device articulates Hans Christian Oersted's 1820 discovery of the magnetic effects of an electric current (Faraday 1844, p. 129). One could speculate—and several did—that the device shows that all forces are convertible (Williams 1964, p. 157). Are such theoretical moves all that is important about the device? Why did Faraday think it necessary to ship ready-made versions of this motor to his colleagues?

Moving immediately from the device to its importance for these various theoretical issues misses its immediate importance. When Faraday made the device, there was considerable disagreement over how it worked. Today, many people still do not know the physics that explains how it works. Both then and now, however, no one denies *that* it works. When Faraday built it, this phenomenon was striking and proved to be very important for the future development of science and technology. Whatever explanations would be offered for the device, and more generally for the nature of "electromagnetical motions," would have to recognize the motions Faraday produced. We don't need a load of theory (or indeed any "real" theory) to learn something from the construction and demonstration of Faraday's device. Or to put it another way, we learn by interacting with bits of the world even when our words for how these bits work are inadequate.

This point is more persuasive when one is confronted with the actual device. Unfortunately, I cannot build a Faraday motor into this book; the reader's imagination will have to suffice. But it is significant that Faraday did not depend on the imaginations of his readers. He made and shipped "pocket editions" of his newly created phenomenon to his colleagues. He knew from his own experience how difficult it is to interpret descriptions of experimental discoveries. He also knew how difficult it is to fashion even a simple device like his motor and have it work reliably. The material product Faraday sent his colleagues encapsulated his considerable manipulative skill—his "fingertip knowledge"—in such a way that someone without the requisite skill could still experience the new phenomenon firsthand. He did not have to depend either on the skills of his colleagues or on their ability to interpret a verbal description of his device. He could depend on the ability of the device itself to communicate the fact of the phenomenon it exhibited.

3. INSTRUMENT EPISTEMOLOGY

I conclude from this that there is something in the device itself that is epistemologically important, something that a purely literary description misses. The epistemological products of science and technology must include such stuff, not simply words and equations. In particular, they must include instruments such as Faraday's motor.

Understanding instruments as bearers of knowledge conflicts with any of the more-or-less standard views that take knowledge as a subspecies of belief (Bonjour 1985; Goldman 1986; Audi 1998). Instruments, whatever they may be, are not beliefs. A different approach to epistemology, characterized under the heading "growth of scientific knowledge," also does not accommodate instruments; such work inevitably concentrates on *theory* change (Lakatos 1970; Lakatos and Musgrave 1970; Popper 1972; Laudan 1977). While I examine some instruments that might be understood in terms similar to theories (e.g., models in chapter 2), instruments generally speaking cannot be understood in such terms. Even recent work on the philosophy of experiment that has focused on the literally material aspects of science either has adopted a standard proposition-based epistemology or has not addressed epistemology.[1] This book aims to correct this failure and to present instruments epistemologically.

This project raises a variety of problems at the outset. There are conceptual difficulties that, for many, seem immediately to refute the very possibility that instruments are a kind of scientific knowledge. We are strongly wedded to connections between the concepts of knowledge, truth, and justification. It is hard to fit concepts such as truth and justification around instruments. Even work that drops these connections finds substitutes. Work on the growth of scientific knowledge does not require truth—"every theory is born refuted." Instead, we have "growth of scientific knowledge" expressed in terms of verisimilitude (Popper 1972), progressive research programs (Lakatos 1970), and the increasing problem-solving effectiveness of research traditions (Laudan 1974). In chapter 6, I develop substitutes for truth and justification that work with instruments.

Prior to these philosophical problems are difficulties arising from the very concept of a scientific instrument. At the most basic level, this is not a unitary concept. There are many different kinds of scientific instrument. What is worse, the different kinds work differently epistemologically. Models, such as Watson and Crick's ball-and-stick model of DNA, clearly have a representative function. Yet devices such as Faraday's motor do not; they perform. Measuring instruments, such as thermometers, are in many ways hybrids; they perform to produce representations. Consequently, before I take on the philosophical issues of truth and justification, I consider these three types of instrument: models (chapter 2); devices that create a phenomenon (chapter 3); and measuring instruments (chapter 4). I do not claim that this is a philosophically exhaustive or fully articulated typology of instruments or instrumental functions. I do claim significant epistemological differences for each type, differences requiring special treatment.

These categories have histories. Indeed, the very category of scientific instrument has its own history (Warner 1994). The self-conscious adoption of instruments as a form of scientific knowledge has a history. I thus argue in chapter 5 that a major epistemological event of the mid twentieth century has been the recognition by the scientific community of the centrality of instruments to the epistemological project of technology and science. My arguments for understanding instruments as scientific knowledge have, then, to be understood historically. While I use examples scattered through history, my goal is neither to provide a history of scientific instruments nor to argue for the timeless significance of this category. To understand technology and science *now*, however, we need to construct an epistemology capable of including instruments.

4. TEXT BIAS

Instrument epistemology confronts a long history of what I call text bias, dating back at least to Plato, with what is commonly taken as his definition of knowledge in terms of justified true belief. To do proper epistemology, we have to "ascend" from the material world to the "Platonic world" of thought. This may reflect Plato's concern with the impermanence of the material world and what he saw as the unchanging eternal perfection of the realm of forms. If knowledge is timeless, it cannot exist in the corruptible material realm.

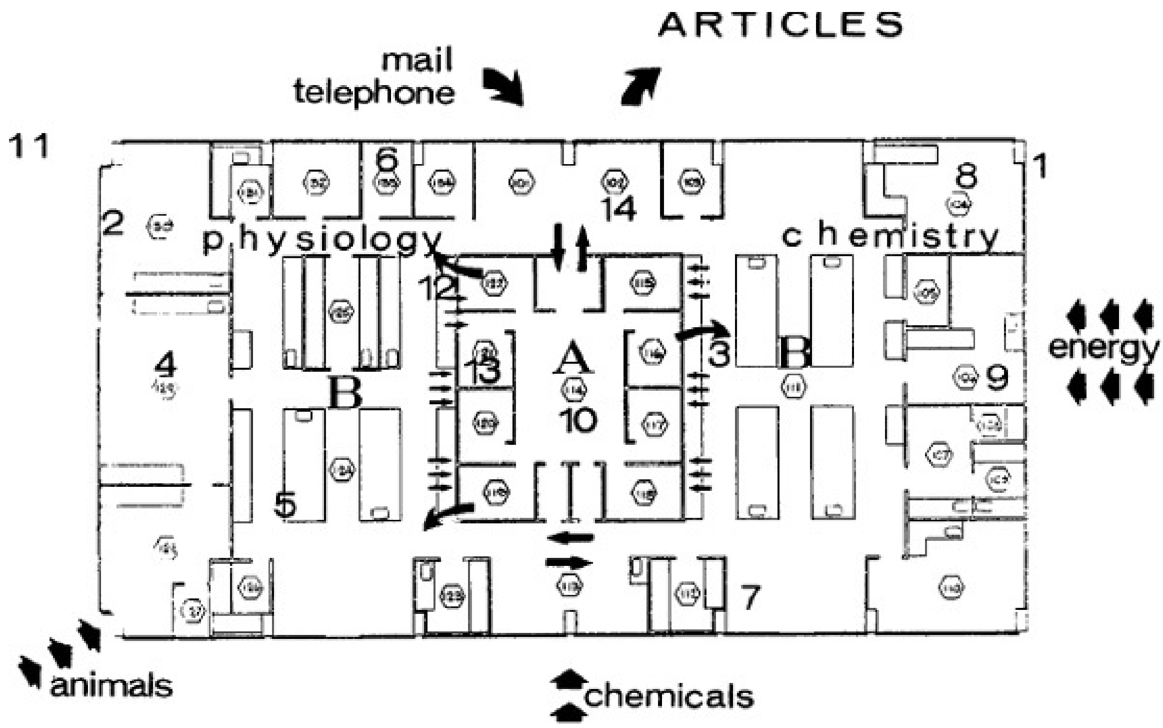

FIGURE 1.2 Laboratory blueprint (from Latour and Woolgar 1979). Reprinted by permission of Sage Publications.

This strikes me simply as prejudice. "It is unfortunate that so many historians of science and virtually all of the philosophers of science are born-again theoreticians instead of bench scientists," Derek de Solla Price writes (1980, p. 75), which is my reaction exactly. Philosophers and historians express themselves in words, not things, and so it is not surprising that those who hold a virtual monopoly over saying (words!) what scientific knowledge is, characterize it in terms of the kind of knowledge with which they are familiar—words.

Prejudice it may be, but powerfully entrenched it is too. The logical positivists were obsessed with "the languages of science" (Suppe 1977). But text bias did not die with them. Consider figure 1.2., taken from Bruno Latour and Steve Woolgar's seminal postpositivist book *Laboratory Life* (1979). Here is the function of the laboratory. Animals, chemicals, mail, telephone, and energy go in; articles go out. The picture Latour and Woolgar present of science is thoroughly literary. "Nature," with the help of "inscription devices" (i.e., instruments), produces literary outputs for scientists; scientists use these outputs, plus other literary resources (mail, telephone, preprints, etc.), to produce their own literary outputs. The material product the scientists happened to be investigating in Latour and Woolgar's study—a substance called "TRF"—becomes, on their reading, merely an instrumental good, "just one more of the many tools utilized as part of long research programmes" (Latour and Woolgar 1979, p. 148).

This picture of the function of a laboratory is a travesty. There is a long history of scientists sharing material other than words. William Thompson sent electric coils to colleagues as part of his measurement of the ohm. Henry Rowland's fame rests on the gratings he ruled and sent to colleagues. Chemists share chemicals. Biologists share biologically active chemicals—enzymes, etc.—as well as prepared animals for experiments. When it is hard to share devices, scientists with the relevant expertise are shared; such is the manner in which E. O. Lawrence's cyclotron moved beyond Berkeley. Laboratories do not simply produce words.

There is much to learn from Latour and Woolgar's *Laboratory Life,* as well as from the subsequent work of these authors. Indeed, Latour and Woolgar are important because they do attend to the material context of laboratory life. But, continuing a long tradition of text bias, they misdescribe the telos of science and technology exclusively in literary terms. Although the rhetoric with which they introduce their "literary" framework for analysis seems new, even "postmodern," it is very old. Once again scholars—wordsmiths—have reduced science to the mode with which they are most familiar, words.

5. SEMANTIC ASCENT

A considerable portion of David Gooding's *Experiment and the Making of Meaning* (1990) focuses on Michael Faraday's experimental production of electromagnetic rotations—the motor I started with. Given this focus, one might suspect that Gooding would see the making of phenomena—such as that exhibited by Faraday's motor—as one of the key epistemological *ends* of science, but he does not. The first sentences of his book are instructive:

> It is inevitable that language has, as Ian Hacking put it, mattered to philosophy. It is not inevitable that practices—especially extra-linguistic practices—have mattered so little. Philosophy has not yet addressed an issue that is central to any theory of the *language* of observation and, therefore, to any theory of science: how do observers *ascend* from the world to talk, thought and argument about the world. (p. 3; emphasis added)

Scientists "ascend" from the world to talk about the world, from instruments to words, from the material realm to the literary realm, according to Gooding. Semantic ascent is the key move in experimental science. Words are above things.

As with Latour and Woolgar, I do not mention Gooding's use of "semantic ascent" to criticize him, for the problem of how words get tied to new bits of the world is important and Gooding has much of great interest and value to say about it. But thinking in terms of the metaphor of ascent implies a hierarchy of ultimate values. It turns our attention away from other aspects of science and technology that are equally important.

It is instructive to see how Gooding discusses Faraday's literary and material products. Faraday accomplished two feats. He built a reliable device and he described its operation. Gooding writes: "[T]he literary account places phenomena in an objective relationship to theories just as the material embodiment of the skills places phenomena in an objective relation to human experience" (p. 177). Faraday's descriptions—his literary "ascent"—"places phenomena in an objective relationship to theories." Analogously, his material work—his device—“places phenomena in an objective relation to human experience.”

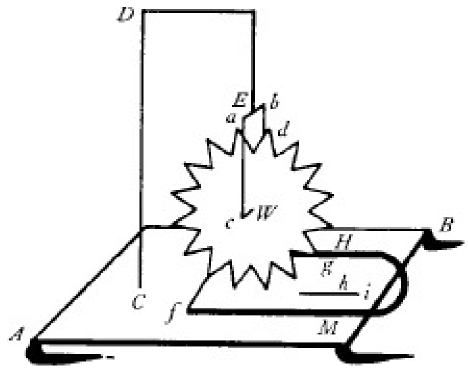

FIGURE 1.3 Peter Barlow’s 1821 star electric motor (from Faraday 1971). Reprinted by permission of the Cambridge University Press.

But “human experience” is the wrong concept. Faraday’s descriptions could speak to theory. In doing so, they could call on the power of logic and contribute to knowledge. We need an analogously detailed articulation of how Faraday’s material work could contribute to knowledge. “Human experience” ducks this responsibility. We can and should say more, and in more detail, about what the material work had “objective relations” with. Avoiding doing so is a symptom of the disease of semantic ascent.

Faraday’s device had a good bit to “say.” The apparatus “spoke” objectively about the potential for producing rotary motion from electromagnetism, which could be developed through material manipulations, starting with the apparatus as a material given. Six months after Faraday made his device, Peter Barlow produced a variant (fig. 1.3) using a star-shaped wheel.

Current runs from one “voltaic pole” to the star’s suspension *[abcd]* through the star to the mercury bath *[fg]* and thence to the other voltaic pole. A strong horseshoe magnet [*HM*] surrounds the mercury bath and, as Barlow put it in a letter to Faraday, “the wheel begins to rotate, with an astonishing velocity, and thus exhibits a very pretty appearance” (Faraday 1971, p. 133, letter dated March 14, 1822).

It is another step to figure out how to create such rotary motion without the use of mercury. Then we might have something useful. There is a significant story here, a story not primarily about the evolution of our words and equations but about material manipulations. The story involves many players and a full telling would not serve much purpose here (see King 1963; Gee 1991). It involves the invention of the electromagnet—developed by William Sturgeon, among others, and considerably improved by the early American physicist Joseph Henry. From the electromagnet to the electric motor is another step, one taken by several people independently (King 1963, pp. 260–71).

The story of one of the claimants to inventing the electric motor, Thomas Davenport, a Vermont blacksmith, is instructive (see Davenport 1929; Schiffer 1994). In 1834, Davenport was intrigued by news of a powerful electromagnet built by Professor Henry that was capable of lifting a common blacksmith's anvil. Davenport traveled some distance from his home in Vermont to Rennselaer in Troy, New York, to see a demonstration of the electromagnet. He was amazed and entranced with its possibilities. A year later, Davenport succeeded in building a motor capable of driving a seven-inch-diameter wheel at thirty revolutions per minute (see fig. 1.4).

The motor works by switching the polarity of four electromagnets in synchronicity with the motion of the wheel so that the wheel is always drawn forward. (A similar technique is used to make the cyclotron work; see chapter 3.) All of this was accomplished despite the fact that Davenport did not know electromagnetic theory. When he first saw Henry's electromagnet, he had never heard of any of the main contributors to the science of electromagnetism. But he did have an appreciation for the phenomenon exhibited by the electromagnet, and he was able to use this knowledge—presented by the device itself—to make other devices. Davenport was interested in developing devices that would have practical utility, and he did succeed in using his motor to drive a printing press (Schiffer 1994, p. 64). But Davenport's motor also expresses a further articulation of knowledge of electromagnetic phenomena.

Semantic "ascent" prevents us from attending to those pieces of the history of science and technology that do not immediately speak to theory. Yet, as is clear from several of the examples discussed in this book, maneuvers in the material realm are central to the progress of science and technology. The more basic point here is that the material realm provides a space within which work can be done. Exactly what is done in this space frequently—although not always—depends on available theory. But that theory also frequently turns out to be erroneous. This does not bring work to a halt. On the contrary, work can go forward independent of theory or with controversial and/or erroneous theory. Many new instrumental—and subsequently valuable—technological developments have resulted from work based on erroneous theory. Furthermore, theoretical advance frequently follows on instrumental advance.

FIGURE 1.4 Thomas Davenport’s electric motor, patented in 1837 (from Davenport 1929). Reprinted by permission of the Vermont Historical Society.

6. MULTIPLE EPISTEMOLOGIES

A primary consequence of the epistemological picture I am presenting here is that no single unified account of knowledge will serve science and technology. In advancing a materialist account of epistemology—thing knowledge—I do not also argue negatively that propositional and/or mentalistic accounts of knowledge are wrong. On their own, however, they do not provide a sufficient framework for an adequate epistemology of technology and science. More is needed, and a critical part of this is an articulation of how the material dimensions of science and technology do epistemological work. Things and theory can both constitute our knowledge of the world. But I deny that there is a unified epistemological treatment for both. Even within my materialist epistemology, different kinds of instruments constitute knowledge in fundamentally different ways.

Models, which I discuss in chapter 2, work epistemologically in ways that are very similar to theory. They provide representations, and in so doing, they can be assessed in terms of the virtues and vices that are used to assess theoretical representations: explanatory and predictive power, simplicity, accuracy, and so on.

Instruments that create phenomena, such as Faraday's motor, are different and constitute knowledge in a different, nonrepresentational way. Such instruments work epistemologically in a manner that draws on pragmatist conceptions of knowledge as effective action. A fundamental difference, however, is that with instruments, the action has been separated from human agency and built into the reliable behavior of an artifact. I call this kind of knowledge "working knowledge." When we have made an instrument to do something in a particular way and it does it successfully and reliably, we say the instrument works. It is *working knowledge*, and this knowledge is different from the knowledge constituted by models—model knowledge. Working knowledge is the subject of chapter 3.[2]

Measuring instruments, the subject of chapter 4, present a third kind of material knowledge that is a hybrid of the representational and effective action senses of knowledge. Measurement presupposes representation, for measuring something locates it in an ordered space of possible measurement outcomes. A representation—or model—of this ordered space has to be built into a measuring instrument. This can be as simple as a scale on a thermometer. At the same time, a measuring instrument has to do something and do it reliably. It has to work. Presented with the same object for measurement, the instrument must yield outcomes that are the same or can be understood to be the same given an analysis of error. That is, the instrument has to present a phenomenon in the sense of constituting "working knowledge" as discussed in chapter 3.[3] Measuring instruments integrate the two epistemological modes I detail in chapters 2 and 3, model knowledge and working knowledge. I describe this integration as "encapsulated knowledge," where effective action and accurate representation work together in a material instrument to provide measurement.

7. SUBJECTIVE AND OBJECTIVE

Louis Bucciarelli begins his book *Designing Engineers* (1994) with a question raised at a conference he attended on technological literacy: Do you know how your telephone works? A speaker at the conference noted with alarm that fewer than 20 percent of Americans knew how their telephones worked. But, Bucciarelli notes, the question is ambiguous. Some people (although perhaps less than 20 percent) may have an inkling of how sound waves can move a diaphragm and drive a coil back and forth in a magnetic field to create an electric current. But there is more to telephony than such simple physics. Bucciarelli wonders whether the conference speaker knows how his phone works:

> Does he know about the heuristics used to achieve optimum routing for long-distance

calls? Does he know about the intricacies of the algorithms used for echo and noise suppression? Does he know how a signal is transmitted to and retrieved from a satellite in orbit? Does he know how AT&T, MCI, and the local phone companies are able to use the same network simultaneously? Does he know how many operators are needed to keep the system working, or what these repair people actually do when they climb a telephone pole? Does he know about corporate financing, capital investment strategies, or the role of regulation in the functioning of this expansive and sophisticated communication system? (Bucciarelli 1994, p. 3)

Indeed, Bucciarelli concludes, "Does *anyone* know how their telephone works?" (ibid.; emphasis in the original).

Here, following the conference speaker, Bucciarelli uses "know" in a subjective sense. He makes a persuasive case that, in this sense, no one knows how his or her phone works. In the first place, the phone system is too big to be comprehended by a single "subjective knower." In the second place, the people who developed pieces of the hardware and software that constitute the phone system may have moved on to other concerns and forgotten the hows and whys of the pieces they developed. Their "subjective knowledge" may thus be lost. In the third place, complicated systems with many interacting parts do not always behave in ways we can predict in detail. Despite having created them, programmers cannot always predict, and in this sense do not "subjectively know," how their complicated computer programs will behave.

It is, of course, well and proper to engage in what might be called subjective epistemology. This is the attempt to understand that aspect of knowledge that is a species of subjective belief. But if we want to understand technological and scientific knowledge, this is the wrong place to look. This is true for several reasons, the first of which is made clear by Bucciarelli's telephones. If no one—subjectively—knows how the phone system works, the situation with all scientific and technological knowledge is radically worse. The epistemological world of technology and science is too big for a single person to comprehend. People change the focus of their research and forget. Expert knowledge systems transcend their makers.

There is a second important reason why the epistemology of technology and science should not be sought at the level of individual belief. One of the important defining characteristics of scientific and technological knowledge is that it cannot be private. A scientist may do some research that provides strong evidence—in the scientist's view—for some claim. But the claim is not scientific knowledge until it has been subjected to scrutiny by the relevant scientific community and accepted by that community. Scientific and technological knowledge is public in the sense that the knowledge has passed review by peers. With respect to theoretical knowledge, publication in a book or journal article (or preprint, etc.) is the significant point when knowledge claims pass into the public realm of scientific and technological knowledge. In addition to these literary domains of scientific and technological knowledge, there are material domains. When Faraday sent copies of his motor to his colleagues, he was making it available for peer review.

We may be interested, for example, in what Faraday knew—subjectively—when he sent around copies of his motor. This can be important for understanding the history of electromagnetism. We can uncover evidence concerning the papers Faraday read. We can read Faraday's own notes. We thereby can develop an appreciation of his subjective theoretical knowledge. But we also can uncover evidence about Faraday's tactile and visual skills in eliciting the phenomenon that he ultimately built into his motor (see Gooding 1990). We thereby develop an appreciation for Faraday's embodied skills, his know-how and tacit knowledge. Taken together, we come to understand Faraday's subjective knowledge that went into both the writing of his articles and the making of his motor.

Once out of his hands and subject to review by his peers, the articles *and* the motor both pass into the public domain of objective knowledge. An adequate epistemology of science and technology has to include such public objective knowledge. Here are the epistemological products of the subjective engagements of scientists, engineers, and others. These products include theories and the like, written products that occupy the pages of professional journals. But they also include the material artifacts that I consider under the headings of model knowledge, working knowledge, and encapsulated knowledge, in short, thing knowledge.

8. ARGUMENTS AND ORGANIZATION

The multiple material epistemologies that I articulate as thing knowledge rest on several interconnected and mutually supporting arguments. There are four types of argument that run through the various chapters, arguments from analogy, arguments from cognitive autonomy, arguments from history, and, finally, what I call arguments by articulation. The specific instances of each type of argument are different from one another in detail, inasmuch as they serve different epistemological conceptions, and while all the arguments stand as integral parts of the overall picture I present of thing knowledge, it is useful to disentangle the strands and explain how each fits into the organization of the book as a whole.

I present a series of arguments by analogy that the material products of science bear knowledge. In chapter 2, I show how, in several epistemologically important respects, material models function analogously to theoretical contributions to science and technology. Material models can provide explanations and predictions. They can be confirmed or refuted by empirical evidence. I develop these points by appeal to a version of the semantic account of theories where a theory is identified with a class of abstract structures called models. I argue that the material models that are the focus of chapter 2 satisfy all the requirements for abstract models in the sense of the semantic view of theories.

In chapter 3, I present a distinct argument from analogy that deals with "working knowledge." My discussion of Faraday's motor in this chapter foreshadows this argument. We say someone knows how to ride a bicycle when he or she can consistently and successfully accomplish the task. A phenomenon such as that exhibited by Faraday's motor shares these features of consistency and success with what usually is called know-how or skill knowledge. One might say that Faraday's motor "knows how to make rotations," but that overanthropomorphizes the motor. I prefer to say that the motor bears knowledge of a kind of material agency, and I call such knowledge "working knowledge." The analogy runs deeper. We are frequently unable to put into words our knowledge of how to do something like ride a bicycle; it is tacit knowledge. We find a similar situation with instruments such as Faraday's motor, and from two points of view. From an anthropomorphic point of view, the motor articulates nothing in words. But from the point of view of its maker—Faraday, in this case—it was also difficult to articulate how the phenomenon came about. Yet, as in the case of bicycle riding, it is clear that the instrument presents a phenomenon, that it works. The action is effective in a general sense, even lacking a verbal articulation for it. The knowledge resides in the regular controlled action of the instrument. The instrument bears this tacit "working knowledge."

A different collection of arguments that runs through *Thing Knowledge* turns on what can be called the cognitive autonomy of instruments. Davenport learned something from his examination of Henry's electromagnet. He then took what he learned and turned it into another, potentially commercially useful, device. He did this while ignorant of theory and unable to express in words either what Henry's electromagnet had taught him or what he was doing with this knowledge. In chapter 2, I present a variant of this argument. Here we see how James Watson's ability to physically manipulate cardboard models of DNA base pairs led to his discovery of base-pair bonding. Watson employed a distinct "cognitive channel" from the consideration and manipulation of theoretical or propositional material. Variants of this argument appear in other guises in chapters 3, 4, 7, and 8. In a nutshell, the point is that making is different from saying, and yet we learn from made things and from the act of making. Cognitive content is not exhausted by theory, and for the same reason, epistemic content should not be exhausted by theory either. This is, perhaps, the core meaning of the epigraph to chapter 6, by Richard Feynman, "What I cannot create I do not understand." Feynman subjectively knew something through his efforts to create it, after which it carried the objective content of this knowledge in a way that might be subjectively recovered by someone else, just as Henry's electromagnet had meaning for Davenport.

A lot of *Thing Knowledge* is historical and my use of history serves a third collection of arguments for the epistemological standing of instruments. There is, in the first place, the argument that we miss a tremendous amount of what is epistemologically significant in the history of science and technology if we limit our examination to the history of theory. Carnot cycles in thermodynamics are the cycles that were being traced out by steam engine indicators in the twenty years preceding Sadi Carnot's and Émile Clapeyron's work on thermodynamics (see chapter 8 for details). The examples in the rest of the text all aim to show how significant the development of instrumentation has been and how this development proceeds in partial (and sometimes nearly complete) independence of theory.[4] In chapter 5, I discuss a specific transformation in the history of analytical chemistry during the middle years of the twentieth century. Here scientists came to understand that the development of instruments was a central component to the progress in our knowledge of the world. This was the time when Ralph Müller wrote the lines that serve as the epigraph for this book: "the history of physical science is largely the history of instruments" (Müller 1940, p. 571).

At the end of the day, the fundamental argument for the epistemological place of instruments is my articulation of how instruments do epistemological work. This concern drives the organization of the book.

I start with three chapters articulating three different ways in which instruments bear knowledge, first as a material mode of representation, then as a material mode of effective action, and finally as a material mode of encapsulated knowledge synthesizing representation and action. Chapter 5 examines the historical evidence of the coming to scientific self-awareness that instruments bear scientific knowledge. These four chapters, together with the introductory first chapter, make the case that instruments need to be understood epistemologically on a par with theory.

Chapter 6 develops a philosophical theory of knowledge that is up to this task. Here I extend and modify Karl Popper's account of objective knowledge to accommodate instruments as elements of a neo-Popperian "world 3" of objective knowledge. This is the most theoretical of the chapters, and as an immediate antidote to the theory of chapter 6, I focus on the specifically material aspects of thing knowledge in chapter 7. The final three chapters examine three different respects in which thing knowledge shifts our understanding of science and technology.

Collectively, the point of the various chapters is to articulate a picture of why and how instruments should be understood epistemologically on a par with theory. While the various arguments aim to persuade readers of this conclusion, it is the overall picture that must seal the deal. Beyond why instruments should be understood as knowledge bearers, I show how they do this and what the consequences are.

9. BEYOND SCIENCE TO TECHNOLOGY

The kind of epistemology that I advocate here brings out relationships that, while of recognized importance, have not found a comfortable place in the philosophy of science and technology. The idea that engineers and industrialists simply take and materially instantiate the knowledge provided by science cannot stand up to even the most cursory historical study. James Watt's work on steam engine instrumentation—specifically the indicator diagram—made a seminal contribution to the development of thermodynamics (chapter 8). Yet without a broader understanding of epistemology, where instruments themselves express knowledge of the world, alternatives to this notion of "applied science," to the idea of engineering and industry as epistemological hangers-on, are difficult to develop.

"Craft knowledge," "fingertip knowledge," "tacit knowledge," and "know-how" are useful concepts in that they remind us that there is more to knowing than saying. But they tend to render this kind of knowledge ineffable. Instruments have a kind of public existence that allows for more explicit study. My intention is not to downplay the significance of "craft knowledge" and the rest. On the contrary, I believe that an analysis of instruments as knowledge provides insight into this difficult and important epistemological territory.

The most immediate consequence of recognizing instruments as knowledge is that the boundary between science and technology changes. Recent science studies scholarship has recognized a more fluid relationship between science and technology than earlier positivist and postpositivist philosophy of science. Still, it is to theoretical science that one turns to examine *knowledge*. Previously ignored contributions of craftsmen and engineers are now understood to have provided important, and in many cases essential, contributions to the growth of scientific knowledge. But it is theory that is seen to be growing. Davenport's story is a sidebar.

The picture I offer here is different. I see developments of things and of theory as being on a par. In many cases, they interact, sometimes with beneficial results all around, but in many cases, too, they develop independently, again sometimes with beneficial results. Work done in industry, putting together bits of the material world, is as constitutive of knowledge as work done by "theoretical scientists." Some of it is fundamental (John Harrison's seaworthy chronometer, perhaps [Sobel 1995]); some of it is less so (the translucent case for Apple's iMac, perhaps). In this sense, material contributions are not different from theoretical contributions—which run the gamut from Einstein's general theory of relativity to psychotherapeutic notions such as the idea that subliminal exposure to the words "Mommy and I are one" will improve behavior.[5]

There are, however, important differences between work with theory and work with things. Things are not as tidy as ideas. Plato was exactly right on this point. Things are impermanent, impure, and imperfect. Chapter 7 concerns these differences between things and ideas and the epistemological ramifications of these differences. In part, I argue there that many instruments hide the very materiality they are made from. The ideal measuring instrument provides information about the world that can be trusted and acted upon. The instrument performs semantic ascent for us, providing output that is useful in the commerce of ideas. The instrument renders the materiality of the world transparent, and, indeed, it renders the materiality of thing knowledge transparent. In the information age, we like to pretend that we can live entirely in our heads, or, rather, in the data.

Recognizing instruments as bearers of knowledge provides valuable conceptual space within which to fruitfully address vexing problems. The last two chapters concern two such problems.

Chapter 9 focuses on mechanical objectivity, juxtaposing the mechanical grading widely used in aptitude tests (such as the Scholastic Aptitude Test, or SAT) with instrumental approaches to chemical analysis. At issue here is a profound question of what kinds of assessments or measurements deserve our trust, and why. Understanding how knowledge is encapsulated in our instruments provides insight into the allure of mechanical objectivity. By encapsulating knowledge in our measuring instruments, these methods minimize the role of human reflection in judgment. They offer a kind of "push-button objectivity" where we trust a device and not human judgment. How many people check their arithmetic calculations with an electronic calculator?

This has radically changed our world. Putting our faith in "the objectivity" of machines instead of human analysis and judgment has ramifications far and wide. It is a qualitatively different experience to give birth with an array of electronic monitors. It is a qualitatively different experience to teach when student evaluations—"customer satisfaction survey instruments"—are used to evaluate one's teaching. It is a qualitatively different experience to make steel "by the numbers," the numbers being provided by analytical instrumentation.

Chapter 10 examines a different respect in which the appearance of thing knowledge in the mid twentieth century is radically changing our world. Thing knowledge casts into sharp relief a conceptual and cultural problem that fundamentally threatens our "intellectual commons": namely, what the value of knowledge is and how it should be exchanged. Through the middle of the twentieth century, knowledge expressed as ideas was exchanged on fundamentally different terms than commodities. The academic producers of knowledge were paid primarily in terms of recognition, not cash. Recognition is given for knowledge made available in public forums, such as professional journals available in libraries. This can work when the production cost of knowledge is relatively low. Making instruments, however, is expensive, and for this reason they are treated as commodities. This began with the advent of thing knowledge in the middle of the twentieth century, and now we are witnesses to the transformation of all knowledge into commodities. Recognition for important contributions to knowledge is nice, but financial reward in the shape of patent fees and grants has assumed central importance.