6 Thing Knowledge

> What I cannot create I do not understand.
>
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1. DOES IT MATTER?

Does it matter that we call the various devices discussed in chapters 1–4 “knowledge”? Is the scientific instrumentation revolution of chapter 5 a revolution in name only? Why not content ourselves with the observation that much analytical skill can be encapsulated in a direct-reading spectrometer, as described in chapter 4? Why not be content to say that Faraday made a new instrument that provoked the development of our theoretical *knowledge* of electromagnetism and the development of *useful* machines? Why not be content to admire the skills of eighteenth-century orrery makers for their beautiful devices that so closely mimicked the motions of the heavenly bodies? What is gained in collecting spectrometers, electromagnetic motors, orreries, and a vast array of material products of cunning, skill, insight, understanding and luck under the heading of knowledge, along with theories, great and small, that warrant being called contributions to our technological and scientific knowledge of the world?

Skeptical questions such as these may be variously interpreted. They may express hostility to all knowledge talk. Some may argue that knowledge talk at best covers over the detailed, contingent, social and political negotiations that lie behind establishing one set of propositions and practices instead of other sets of propositions and practices. These questions may also express a neutral attitude to knowledge talk. Talk of knowledge if you like, but there is no value added in doing so. Nothing changes if we call Einstein’s general theory of relativity or Jason Saunderson’s direct reader contributions to knowledge. No work is done beyond noting the various particular—historically contingent—reasons why Einstein’s theory and Saunderson’s instrument were enfolded into the ongoing theoretical and instrumental practices of the cultures that embraced them. Finally, these questions may express skepticism about extending knowledge talk from theories—where historical and philosophical precedents have long established such talk—to parts of the material world. Knowledge concerns a special kind of human belief, belief that can be justified in some special—perhaps even historically evolving—manner. Material instruments certainly cannot be beliefs, and hence it makes no sense to speak of them as knowledge.

A general hostility to knowledge talk has been one of the salutary contributions of certain strains of the "strong programme in the sociology of scientific knowledge" (Pickering 1995). I say "salutary," not because I agree, but because these arguments force us constructively to reexamine issues that lie at the foundations of the epistemology of science and technology.

It is possible for a focus on epistemology to distort one's understanding of the history of science. Such a focus easily slips into a view of rational—epistemological—forces behind the progress of science in battle with irrational—social, political, financial, and so on—forces holding back the progress of science. But it is not necessary to make this move. An epistemologist can acknowledge the importance and positive value of nonepistemological forces in the development of science but still want to mark a distinction. World War II certainly was the key reason for the development of Saunderson's direct-reading spectrometer (see chapter 4), along with many other analytical instruments. The war may even have been responsible for a shift in the very category of what it is to know—as I argue in chapter 5. But the development of the photomultiplier tube also played a key, indeed necessary, role in the development of the direct-reading spectrometer. The war and the photomultiplier tube made different kinds of contributions to the development of technology and science. Marking the distinction between these two different kinds of contribution need not imply anything about the relative importance or value of either.

Epistemology can grant the importance of social, political, and financial contributions to establishing theories, practices, and instruments. Epistemology can grant the historicity of the categories of knowledge and the justifications for its acceptance. Such concessions, if, indeed, it makes sense to call them concessions, do not necessarily impugn the project of epistemology. In writing "What I cannot create I do not understand" on his chalkboard, Richard Feynman was posing a challenge to epistemologists to articulate what their understanding amounts to.[1] If Feynman's understanding was a product of his times—and it would not have been Newton's understanding—it is an epistemological challenge to articulate the history of this transformation. The fact that nonepistemological forces may play important or even determinative roles in how science and technology develop implies neither that epistemological forces play no role (surely a historically contingent question) nor that it is impossible to draw a distinction between the epistemological and the nonepistemological, to analyze the difference between them.

How we mark the distinction between the epistemological and the nonepistemological makes a difference. Practices are affected by the way the distinction is made. A century ago, it was widely held on theoretical and empirical grounds that the only "natural" kind of variation was variation that formed a Normal (Gaussian, or "bell-shaped") distribution. Karl Pearson, because of his commitment to a now discredited positivism, argued for and established the point that natural variation can be other than Normal. Pearson's epistemology—even though it would be unlikely to persuade many people today—mattered to the future of statistical science (see D. Baird 1983). Pearson presents one example, but many others could be found. How a particular scientific community conceptualizes knowledge affects how knowledge develops in that community. This surely is one of the central lessons in Peter Galison's *Image and Logic* (1997).

The material epistemology I articulate here has important implications. The boundary between science and technology, and perhaps even the contemporary validity of that boundary, is affected by a shift to include the material as epistemological. Faraday's material manipulations, and not simply their bearing on theory, become part of the history of scientific *knowledge*. So does Thomas Davenport's work constructing an electromagnetic motor (see chapter 1). Thing knowledge has implications for how we regard the work of engineers—for the category of "applied science." It could have implications for the kind of work that is rewarded in institutional settings: publish or perish, or demo or die? When we create scholastic aptitude tests, we create a powerful force for change in school curricula (see chapter 9). Does scholastic aptitude include the ability to make something? If not included in scholastic aptitude tests, the teaching of such abilities will be marginalized or lost.

Putting aside these deeper skeptical questions about the very project of epistemology, however, there remains the question of extending the concept of knowledge to include the material products that I focus on in chapters 1–5. In the first place, I have argued that instruments have played roles epistemologically analogous to theories. They have provided a medium in which to express, explore, and develop our understanding. They have provided a medium for explanation and prediction. In the second place, while instruments and theory typically work together, I have presented cases where they have not, where instruments have developed autonomously or in spite of bad theory. Such cases show that it is not possible to reduce the epistemological value of instruments to the epistemological value of theory. Together, these two points argue for finding a way to think of instruments epistemologically on a par with theory. Finally, there is Feynman's remark; creation is essential to understanding. Making is essential for Feynman's brand of subjective knowing. This remark is not an idiosyncratic fluke of Feynman's. It speaks to the epistemological transition of his time, the scientific instrumentation revolution. The situation calls for an epistemological analysis capable of including instruments.

2. DONE AND YET TO DO

So I take it that it does matter how we conceptualize knowledge, and I take it that the examples and arguments of chapters 1–5 call for a conceptualization that includes the material products of science and technology. More than this, the work done in the first five chapters goes some distance toward articulating new material epistemologies. Material models are a material form of representational knowledge. Devices that produce phenomena are instances of working knowledge, a kind of pragmatic knowledge that is constituted by effective action, but effective action with a twist, for the locus of the action is the device itself, not a human being. Measuring instruments present a third kind of material epistemology. They encapsulate in their material form not only both model knowledge and working knowledge but also, in many cases, theoretical knowledge and functional substitutes for human skill. In their material form, measuring instruments integrate all these different kinds of knowledge into a device that is at once both an instance of materially encapsulated knowledge and a source of information about the world.

The epistemological importance of instruments is not ahistorical. To paraphrase H. A. Liebhafsky (see chapter 5 above, end of § 5), science and technology became disciplines devoted to characterization and control during the twentieth century. Characterization is one kind of representation, and control is a matter of effective action. John Taylor (ibid., § 1) has compared what he calls "the second chemical revolution"—which I call "the instrumentation revolution"—with the industrial revolution, in which mass production displaced human craftsmanship. Instruments that encapsulate knowledge take this a step further with the appropriation of human skill and subjective knowledge. The three kinds of thing knowledge presented in chapters 2–4 are the essential components of the instrumentation revolution, in which characterization and control, encapsulating subjective human knowledge and skill in material—instrument—form, is a fundamental component of contemporary scientific-technological knowledge. This is what I call thing knowledge, and the five preceding chapters take the first steps in saying what it is and how it is central to current science and technology.

But much remains to be done. In the first place, I have to address head on the conceptual puzzle that thing knowledge poses to philosophy. It is the thesis of this book that we need to stretch the concept of knowledge to include the things of science and technology. But this stretching requires attention to the broader conceptual landscape. Knowledge has a long history of connection with concepts such as truth justification and belief. What can we say about these concepts in light of a stretched concept of knowledge? The next five sections of this chapter, where I articulate the concept of an instrumental function as a kind of material surrogate for truth, address this concern.

The final six sections of this chapter present and argue for a more general epistemological picture with which to embrace the various material epistemologies I have been concerned with —as well as more traditional proposition-based epistemologies. This picture draws on Karl Popper's "objective knowledge," but with a decidedly non-Popperian materialist basis. I find this neo-Popperian picture both compelling and useful. I know, however, that many find Popper's epistemology implausible at best, and I respond to some of the more fundamental criticisms of Popper in sections 9–12.

More work remains to be done. The new material epistemologies that I advocate have a variety of consequences that take us well beyond epistemology per se. The last four chapters of this book examine four of the most significant consequences to thing knowledge. To come to terms with knowledge borne by things, and not simply ideas or propositions, we have to recognize the difference between things—as a medium—and ideas. There are fundamental differences, and setting them out is the project of chapter 7, "The Thing-y-ness of Things." Thing knowledge has consequences for how we lay down boundaries between science and technology, for how we tell the history of science and technology. Chapter 8, "Between

Technology and Science," presents a history of an instrument, the steam engine indicator, that crossed old boundaries between science and technology. Seen in the context of thing knowledge, the history of the indicator makes more sense than a history based in traditional idea epistemology. Objectivity is another concept that is transformed by thing knowledge. Chapter 9, "Instrumental Objectivity," examines this transformation, with respect to both its promise and its problems. When objectivity resides in instruments, what is the role of human judgment? Finally, an epistemology that includes things changes the economics of epistemic exchange. Chapter 10, "The Gift," examines the nature and ramifications of this change.

3. CONCEPTUAL PROBLEMS WITH MATERIAL KNOWLEDGE

I claim that material products such as Davenport's motor bear knowledge, and that the kind of knowledge they bear is typically different from the kind of knowledge borne by theories. But the concept of knowledge is tied to other concepts. A well-worn road in epistemology speaks of justified true belief. My project is one of expanding the domain of knowledge, and doing this requires rethinking the concepts with which we analyze knowledge.

Belief is a big problem. Whatever Davenport's motor may be, it is not a belief. It is not that I deny the sense or value of speaking of a person's subjective knowledge, and of doing so in terms of a person's beliefs. Rather, I assert that in addition to subjective belief, we need an analysis of objective knowledge, of knowledge that can be distinguished from its subjective origins. Both subjective and objective points of view are important to epistemology. I take up this relationship in more detail in section 9.

I have never been wedded to a literal use of "truth" in the analysis of knowledge. Here my roots in Popper's and Lakatos's philosophy show (Lakatos and Musgrave 1970; Hacking 1981). "Every theory is born refuted" (Lakatos 1978, p. 5). But there is something about "truth" that is important. Popper writes of truth as a "regulative ideal…that is, of a description which fits the facts" (Popper 1972, p. 120). We should seek true theories, and Popper offers an elaborate theory of verisimilitude as a central component of his method of "systematic rational criticism" (ibid., ch. 2, §§ 8–10). But Popper's theory of verisimilitude has been beset by empirical and conceptual problems, and it has not been persuasive. Still, accuracy remains a regulative ideal of science. We want good representations, true to what we know of the objects they claim to describe.

The fundamentally new contribution, necessary for understanding material knowledge, is that of an instrumental function. Material models, since they operate representationally, can call on the extensive literature on representation, some of which I employ at the close of chapter 2. Working knowledge is not being representational, and it needs something else. Instrumental function is this something else. To motivate and justify this conclusion, I first ask the more fundamental question, "What does knowledge do for us?" In answering this question without presupposing a propositional—ideational or belief-centered—concept of knowledge, we shall be in a position to understand how instrumental function serves to give material devices the values of knowledge.

4. WHAT DOES KNOWLEDGE DO FOR US?

If I want some information about plutonium, I can easily look it up:

> Plutonium. Actinide radioactive metal, group 3 of the periodic table. Atomic number 94. Symbol Pu. This element does not occur in nature except in minute quantities as a result of the thermal neutron capture and subsequent beta decay of ^{238}U; all isotopes are radioactive; atomic weight tables list the atomic weight as [242]; the mass number of the second most stable isotope ($t_{½} = 3.8 \times 10^5$ years). The most stable isotope is ^{244}Pu ($t_{½} = 7.6 \times 10^7$ years). *(Van Nostrand's Scientific Encyclopedia* 1983, p. 2262)

I do not have to read about Glenn Seaborg's discovery of the element in 1940 through the deuteron bombardment of uranium accomplished with UC Berkeley's 60-inch cyclotron. Nor do I have to read about all of the various ways in which the above information has been ascertained and justified. This information has been detached from the context of its discovery and can be used elsewhere without reference to its discovery (which, I note, is lacking in this encyclopedia entry).

This is a feature of scientific knowledge that is of signal importance. Knowledge can detach from its context of discovery to be used elsewhere. It comes with a kind of guarantee that when used appropriately, it can be depended upon. Knowledge is efficacious in this respect. Finally, knowledge comes with a guarantee of a kind of longevity. Knowledge is more than mere opinion, more than a fashionable whim.

To these three ideals—detachment, efficacy, and longevity—I add two others. The first is obvious, but important in ways that emerge in subsequent discussion. Knowledge establishes a relationship between humans and the world. We may assert a fact or develop a detailed picture of "how we think things are." Knowledge serves to connect our thinking with the world—either the world is, is not, or is in certain important respects as we represent it to be. And note that I do not thereby claim there is a single correct representation. There may be more than one adequate representation, more than one expression of our knowledge of some topic.

The last ideal I am concerned with is objectivity. Knowledge stands in a special relationship between an individual and the world, where the world's voice has a kind of priority. I may have wished that Al Gore had won the popular vote in the state of Florida in the 2000 presidential election. But my wishing it were so won't make it so. The votes make it so. "The votes" stand as impartial arbiters between camps with conflicting wishes. They provide an objective standard independent of subjective wishes.

I use the Florida election pointedly, for it was a flawed election that revealed the difficulty with the idea of the world's voice having priority. How is the world's voice "heard"? In

Florida, there were moves and countermoves. The wishes of the various camps directed the reading of the chads on the ballots. Some are tempted to conclude that that world has no voice. There are only the voices of the warring camps, each enlisting features of a mute world to support projection of its voice. If one accepts this, one cannot be dismayed by the manner in which the election was brought to closure through legal action and the more easily counted votes of nine Supreme Court justices. We should prefer to accept as an ideal a different view of the matter: as a matter of objective fact, either Al Gore or George Bush did receive more votes in Florida and should have won the election on that basis. Unfortunately, our methods of ascertaining this objective fact were not up to the task. Objectivity, like the other features I have identified, is an ideal.

We have, then, five ideals that encompass core values to knowledge:

1. Detachment: technological and scientific knowledge can detach from its context of discovery
2. Efficacy: technological and scientific knowledge can be depended upon to accomplish appropriate ends
3. Longevity: technological and scientific knowledge can be depended upon into the indefinite future
4. Connection: technological and scientific knowledge establishes a relationship between the world and us
5. Objectivity: "the world's voice" has a kind of priority in the relationship between the world and us

These are ideals. As such, we don't expect any specific claim to knowledge to live up to them without controversy and struggle. But also as ideals, they tell us why knowledge is important, and why, in the domain of material knowledge, instrumental functions are important.

5. INSTRUMENTAL FUNCTION, MATERIAL TRUTH

Each of the five ideals of knowledge describes important central features of the instrumental functions we develop and deploy in our artifacts. Efficacy falls out almost by definition. When we build an artifact to accomplish some goal, we depend on the efficacy of our material contrivance to accomplish the goal. If it fails to accomplish the goal—if it fails to function—we have to keep at it or abandon the project and/or goal. The point of a material function is to accomplish something, to be efficacious.

Detachment, not quite as obvious as efficacy, is an equally central feature of the functions of our artifacts. Photomultiplier tubes were developed in the late 1930s as part of a research program at RCA. Spectrometry was not RCA's target application. When these tubes were used in a direct-reading spectrometer, their function of sensing light was detached from their original context of development. This "material detachment" is not simple. The quality control on RCA's manufacture of the tubes was relatively loose, and individual tubes had to be individually checked for adequate performance in a spectrometer. Tubes that checked out were expected to perform their function into the foreseeable future.

"Into the foreseeable future" speaks of longevity. Material artifacts are perhaps more prone to wear and tear than theoretical knowledge. They cannot be depended on to work forever. But if we couldn't depend on them to work for a reasonable—sometimes carefully quantified—amount of time, they wouldn't be of much use. Whatever else they are, functions must have material forms that behave as do the phenomena Peirce speaks of in *Pragmatism and Pragmaticism* as "a permanent fixture of the living future."

Functions must have a kind of objectivity too. I may wish that the Ethernet circuitry card in my computer were not broken. I may even behave as if it were not broken, reloading software and replacing other components. But, at the end of the day, if it is broken and I want to connect to an ether network with my computer, I am going to have to find a replacement or substitute for my Ethernet card. Now reliability is not a black-and-white concept. Perhaps my Ethernet circuit has a "flaky" component that only works some of the time. Here we can develop the statistical theory and practice of reliability.

I have saved connection, which seems the simplest feature of knowledge, for last. Both scientific knowledge and engineered function connect us with the world. Theoretical knowledge connects how the world is with how we represent it to be. Functions connect how an artifact behaves with how we want it to behave. Here is an obvious and fundamental feature of functions, but while it may seem to be the simplest function of functions, it is indeed deeply complex and problematic and requires, finally, a closer examination, which I shall put off until section 10.

Roughly speaking, then, I claim that an artifact bears knowledge when it successfully accomplishes a function. This claim requires elaboration, most particularly with respect to the concept of function itself. The concept I employ is relatively thin, stripped of any heavy load of intentional baggage and focused on the reliable, regular predictable performance of the artifact. It might best be characterized in terms of mathematical functions rather than biological or more broadly teleological functions. A function, for me, is a crafted and controlled phenomenon.

There is linguistic evidence to support my association of function with knowledge and truth. Philosophers are accustomed to think of truth in terms of propositions or sentences, and so ignore turns of phrase such as "a true wheel." A golfer has spoken to me of a "true drive down the fairway." Among the more philosophically common senses of "true," we also find "9. Accurately shaped or fitted: *a true wheel*. 10. Accurately placed, delivered, or thrown" (*American Heritage College Dictionary,* 3d ed., s.v.). But a "true wheel" is not true simply because it properly conforms to a particular form; a true wheel spins properly, dependably, regularly. A wheel that is out of true wobbles and is not dependable. Ultimately, it will fail. This sense of "truth" picks out those contrived constellations of materials that we can depend on. A public, regular, reliable phenomenon over which we have material mastery bears a kind of "working knowledge" of the world and "runs true" in this material sense of truth.

The need for the wheel to spin properly to be true immediately intertwines this material sense of truth with the notion of function. Barring aberrant contexts, the basic function of a wheel is to spin smoothly, regularly, and reliably. Of course, we may deploy such a function as a component serving the broader purpose of some device. Bicycle wheels spin to move the bicycle, gyroscope wheels spin to provide a sense of balance. But it is because a bicycle maker can depend on the spinning function of the wheel that the maker can deploy this function to serve the broader goal of locomotion; the same may be said for a gyroscope maker.

Knowledge, expressed in propositions, provides fodder for further theoretical reflection. These resources—sentences with content—are manipulated linguistically, logically, and mathematically. Theoreticians are "concept smiths," if you will, connecting, juxtaposing, generalizing, and deriving new propositional material from given propositional material. In the material world, functions are manipulated. In a spectrograph, photographic film is used to record spectral lines. In a direct-reading spectrometer, photomultiplier tubes replace photographic film. This is a functional substitution. One material truth is substituted for another that serves the same function. Photomultiplier tubes perform the function of intensity recording instead of photographic film. "Instrumenticians" are "function smiths," developing, replacing, expanding, and connecting new instrumental functions from given functions.

6. THICK AND THIN FUNCTIONS

In my analysis, a function couples purpose with the crafting of a phenomenon. A function is a purposeful phenomenon. But adding purposes adds problems. There are problems ascertaining purposes or intentions. Without access to a designer's mind or a design team's interactions, determining the intention behind some part of an instrument can be a difficult matter of reconstruction and interpretation. Reverse engineering is not an automatic process. There are problems with unintended uses. The designers of photomultiplier tubes did not intend their tubes to be used for radar jamming, but they were so used because of the "black current" they produced (see chapter 4). They also were used to check for defective fuses in grenades (White 1961, p. 143). There are problems with intended consequences based on mistaken understandings. M. S. Livingston focused his cyclotron's beam by shimming the magnet, incorrectly thinking that he was fixing irregularities in what he imagined should be a homogeneous magnetic field (see chapter 3). There are problems of unintended consequences. In the early days of word processing, the idea was to decrease, not increase, paper consumption. Football helmets were meant to decrease serious injury. Unfortunately, despite the best intentions, things frequently "bite back" (Tenner 1996).

Function also has a normative dimension, which adds another set of difficulties. In certain respects, the direct-reading spectrometer was better at determining elemental concentrations in samples of metal. It was quicker than photographic spectroscopy or wet chemical methods—enough to make a major difference in the manufacture of metal. Less human labor and judgment were necessary. However, although it was more accurate for many important chemical elements, this was not the case with all of them, and it could be used to analyze only certain preselected elements. It was much more expensive. The direct-reading spectrometer changed forever the role of the chemical analyst in metal manufacture. There never is a simple "worse/better" with the kind of normative judgments involved with functions. Trade-offs are an inescapable part of work in the material world. Consequently, it is difficult to determine how normative judgments were applied in making certain choices in the development of an artifact, and it is more difficult, if, indeed, it is possible at all, to determine what normative judgments *should* be applied.

A full analysis of the role of function in design requires attention to all of these problems. Functional design, like theoretical representation, is a deeply intentional arena.[2] When we speak of the knowledge an engineer has of the artifact he or she is working with or on, we must include the engineer's understanding of the purposes of the various components to the artifact and the overall purpose of the artifact itself. Knowledge of purpose is an essential part of the subjective knowledge engineers must have to make and work with artifacts.

My aim here, however, is not an analysis of the subjective knowledge of engineers. I am concerned with the objective knowledge borne in the artifacts engineers develop and deploy. For these purposes, a "thinner" notion of function suffices. I acknowledge that functions are connected with intentions in some way. But I sidestep a detailed analysis and focus on phenomena. The epistemological work I extract from instrumental function can be accomplished by our crafting a phenomenon. Here we get the ideals of knowledge—detachment, efficacy, longevity, objectivity, and connection.

While we may draw on the concept of a function as used in biology—the function of the heart, for example, is to pump blood—for an analysis of the thicker conception of function, the thinner concept I am interested in draws on a different discipline. A mathematical function, as opposed to a biological function, is an association of values, or, to put it another way, a set of ordered pairs of values. We can talk of how "the function *produces* an output value for a given input value." We can think of a mathematical function in quasi-teleological terms: the x^2 function has the purpose of giving as output the square of a number given as input. But from a definitional, set-theoretic point of view, a function simply is a set of ordered pairs: (1, 1), (2, 4), (3, 9)…. This is how to think about crafted material functions. What we want is a device—an artifact—that reliably associates inputs and outputs, a device that is, in a possible-world kind of way, a set of ordered pairs of inputs and outputs.

Consider the work that went into crafting photomultiplier tubes for use in a spectrometer. As it happens, the tubes were sensitive to exactly where the light struck the initial cathode. They did not instantiate a univocal set of ordered pairs, for a given input of light intensity could be associated with a spread of possible output values (see chapter 4, § 5). Jason Saunderson did not know the reason for this undesirable spread. What to do? By inserting a quartz plate between the light source and the tube's cathode, he "fuzzed" the light over the cathode. This produced a material kind of averaging, with the result that the outputs were more closely univocally tied to the inputs.

As with the other ideals I discuss earlier, material functions do not live up to their ideal mathematical counterparts. We do not have an absolutely straight horizontal line for Saunderson's fixed photomultiplier tubes (curve *c* in fig. 4.7). But this is clearly what he was aiming for: One output associated with one input.

7. JUSTIFICATION

The eliciting, stabilizing, routinizing, even black-boxing, of functions—in my mathematical sense—is hard work. Galison has documented this work of justifying material knowledge in great and fascinating detail (1987, 1997), and Hacking, Buchwald, Gooding, Latour, Pickering, and others have addressed similar points.[3]

Justification of material truths—model knowledge, working knowledge, and encapsulated knowledge—is a matter of developing and presenting material, theoretical, and experimental evidence that connects the behavior of a new material claim to knowledge with other material and linguistic claims to knowledge. In some cases, a phenomenon is sufficiently compelling on its own. Such was the case with Faraday's motor. Typically, however, it is important to connect the phenomena an instrument deploys with other instrumental, experimental, and/or theoretical knowledge. This situates new working knowledge in the field of material and theoretical knowledge. Such connecting work provides depth and justification to new knowledge. Thus, in a report on the first commercial use of a direct-reading spectrometer for steel analysis, a table is included (see table 6.1).

TABLE 6.1 Spectrometer/Spectrograph Calibration

Element	*Chemical Analysis*	*Extremes, Spectrometer*	*Spectrograph % Standard Deviation*	*Spectrometer % Standard Deviation*
Manganese	0.55	0.54–0.56	1.82	1.35
Silicon	0.28	0.27–0.29	1.97	2.46
Chrome	0.45	0.44–0.47	1.92	2.06
Nickel	1.69	1.68–1.71	1.85	0.79
Molybdenum	0.215	0.21–0.22	2.66	1.68

SOURCE: Vance 1949, p. 30. Reprinted by permission of the *Journal of Metals.*

The table shows, first, that for the five elements measured, the range of concentration readings provided by the spectrometer centers on the concentrations found by wet chemical analysis. Secondly, the table shows that for manganese, nickel, and molybdenum, the precision of the spectrometer is better than the spectrograph in terms of percentage of standard deviation. With silicon and chrome, it is the reverse. The table thus connects the behavior of the new instrument with other techniques (wet chemistry) and instruments (a spectrograph).

Work such as that reported in table 6.1 justifies the subsequent use of the new instrument. Analysts can use it with the degree of confidence justified by the data in the table. Another way of thinking about this is that such work justifies the transition to a new material form of knowledge. It ensures the appropriate kind of stability through change. The instrument is *calibrated*, relative to other material and conceptual knowledge, for its range of appropriate—trustworthy—uses.

This is the work of creating instrumental functions, material knowledge. An instrument maker has to produce, refine, and stabilize a phenomenon—working knowledge—that serves some instrumental purpose. These instrumental functions, then, can be manipulated, conjoined, combined, adapted, and modified for the overall purpose of the instrument in question. The behavior of the resulting material device, then, is connected to established apparatus, theories, and experiments. The result is growth in material knowledge.

The fact that it is hard to establish an instrumental function materially has a corollary. Where truth serves as one regulative ideal for theory construction, the regularity and dependability of a phenomenon serve for instrument construction. This is where the material sense of "true"—as opposed to out of true, as in the case of a wobbly wheel—points us in the right direction. "Material truth"—working knowledge—serves as a regulative ideal for material knowledge, just as "theoretical truth" serves as a regulative ideal for theoretical knowledge.

8. POPPER'S OBJECTIVE KNOWLEDGE

Thus far I have argued that we need to understand instruments themselves as knowledge bearers, on a par with theory. I have articulated three different kinds of knowledge borne by instruments, and I have offered several thing-centered substitute concepts for the key epistemological concepts of truth and justification. I close this chapter with a more general epistemological picture that speaks of objective knowledge, borne by, among other things, things—scientific instruments. My picture draws on Karl Popper's account of "objective knowledge" or "epistemology without a knowing subject" (Popper 1972, ch. 3). But where Popper restricts his epistemology to the "world of language, of conjectures, theories, and arguments" (ibid., p. 118), I include things.

Popper's ontology includes three distinct, largely autonomous, but interacting "worlds" (ibid., p. vii and ch. 3). The first is the material world of stones and stars—"the first world," or "world 1." Next is the world of human (or possibly animal) consciousness, of beliefs and desires—"the second world," or "world 2." Finally, Popper proposes a "third world," or "world 3," of objective knowledge. Popper's third world consists of the content of the propositions that make up the flow of scientific discourse. Each world emerges from, and is largely autonomous from, its predecessor world. Conscious states may require material instantiation, but they are not explicable in purely material terms. Objective knowledge may depend on human consciousness, for conscious humans (typically) produce knowledge, but objective knowledge is not explicable purely in mental terms.

Popper's third world may sound dubiously metaphysical, but the kinds of objects he populates it with bring it down to earth. These include "theories published in journals and books and stored in libraries; discussions of such theories; difficulties or problems pointed out in connection with such theories; and so on" (ibid., p. 73). It is not the physical marks on journal paper that Popper points to but the assertions these physical marks express.

There is an ontological issue that differentiates my epistemological picture from Popper's. It makes some sense to think of language in immaterial terms. "The proposition expressed by the sentence, 'There is no highest prime number'" surely is a candidate for an immaterial object. It is quite natural to think of propositions, ontologically, as something akin to Plato's forms. The material products of science and technology with which I am concerned most certainly are material, and the "idea of a thing" cannot be identified with the thing itself. In Popper's terms, the material creations would seem to occupy world 1. I claim they are in world 3. I conclude this chapter—in section 13—considering this ontological problem.

9. SUBJECTIVE AND OBJECTIVE REVISITED

Popper strongly criticizes those whom he calls "belief philosophers," who "studied knowledge… in a subjective sense—in the sense of the ordinary usage of the words 'I know'" (1972, p. 108). Such a focus, says Popper, leads to irrelevancies. Our focus should rather be on "*knowledge or thought in an objective sense*, consisting of problems, theories, and arguments as such. Knowledge in this objective sense is totally independent of anybody's claim to know; it is also independent of anybody's belief, or disposition to assent; or to assert, or to act" (ibid., pp. 108–9; emphasis in original). Imre Lakatos's rational reconstructions of scientific research programs radically extend Popper's proposal for objective epistemology (Lakatos 1970; see also Hacking 1983a, ch. 8).

I prefer a less extreme version of objective epistemology. Popper focuses on problems, theories, and arguments, the stuff that might be found preserved in libraries. In most cases, the sentences that make up these problems, theories, and arguments are connected with beliefs held at some time singly or jointly by the author(s) of the sentences. People, with their subjective beliefs, are almost always involved in one way or another with objective knowledge. Popper's example of tables of logarithms produced by machine and never used by humans (see § 10 below) is exceptional and probably related to beliefs in a second-order analysis. In many cases, the sentences preserved in libraries are one way to understand the beliefs of the actors involved. Thus, my brief reconstruction of Livingston's beliefs about the operation of his cyclotron in chapter 3 is based on the written historical record. But it goes beyond the specific sentences in the record, and Livingston's beliefs are a useful historical category on which to pin the reconstruction.

There is a similar relationship between the things we make and a complex of human capacities that include skills, know-how, the ability to visualize, and, indeed, beliefs, the nexus often referred to as "tacit knowledge." David Gooding's discussion of the work Faraday did that led up to the making of his electromagnetic motor provides insight into exactly this relationship (1990). Gooding's reconstruction of Faraday's work, using the written record to direct reenacting this work, provides valuable insight into the motor Faraday ultimately made and its relationship to Faraday's skills, know-how, and so on. Both the more objective epistemological object—Faraday's motor—and the more subjective epistemological object—Faraday's skills, know-how, and so on—provide insight into Faraday's knowledge and the knowledge borne by his work. Understanding either the subjective or objective objects helps one to understand the other.

With these concessions to critics of Popper in mind, I nonetheless agree with the thrust of Popper's push for a focus on objective epistemological objects. There are several reasons for this.

Objective epistemological objects, sentences, and things are public. In principle, they are open to examination by anyone. For this reason, they can provide insight into the more private domains of beliefs and skills. This surely is one of the reasons why work in artificial intelligence promises insight into natural intelligence. Artificial intelligence is public, open to scrutiny and manipulation in a way that natural intelligence is not. Harry Collins and Martin Kusch's theory of action presents a theory of public behaviors as a way to understand skill and know-how and our relationships with machines (Collins and Kusch 1998).

In a similar vein, historical reconstruction must depend on evidence that can be examined. For the most part, this consists of texts, although artifacts have increasingly become important. Klaus Staubermann's work presents an interesting dialectic between objective and subjective (1998). Staubermann recreated Karl Friedrich Zöllner's nineteenth-century astrophotometer, starting with the public record—both written and artifact. He made a public object and used it to rework Zöllner's experiments. The result is insight into Zöllner's skills, both in making and in using the instrument. But Staubermann's insight into this subjective epistemological object—Zöllner's skills and beliefs—was then reflected back and provided a deeper understanding of the public materials, written and artifact, that were the basis of early astrophysics.[4]

With both historical reconstruction and the contemporary construction of theory, objective epistemological objects play an essential role. While we do not have to join Popper in abandoning subjective epistemological objects, the fact that objective objects can be shared is of fundamental importance.

Objective epistemological objects are also important because they are what can qualify as scientific knowledge. Individual beliefs might at best be called "candidate claims" to scientific knowledge.[5] Individual skills might lead to reliable instruments, but in themselves, they do not qualify as scientific knowledge. It is the community that determines what scientific knowledge is, and communities have to act on public—objective—objects.

Related to this point is the fact that scientific knowledge transcends the subjective beliefs and skills of any individual. This is true in the simple sense that there is more "known" than any single person could subjectively know. But it is also true in the more complicated sense that the tools we have for making beliefs public—speaking, writing, engaging in dialogue—allow us to articulate beliefs in a way that is not possible purely subjectively. My beliefs about Livingston's cyclotron, for instance, develop and crystallize as I write about Livingston's cyclotron. Writing enables us to build more content into our beliefs, creating objective epistemological objects in the process.

A similar point can be made about the tools we have developed to work materials, which dramatically exceed the level of our skills and know-how. As I write, Bostonians are remaking their city, and cranes tower over the Boston skyline. They call it "the big dig." It is a vast project to build a tunnel under the city to remove traffic from city streets; elevated expressways will be a thing of the past.[6] Huge projects such as this, of course, involve a tremendous amount of politics. They involve selling visions of a future Boston to skeptics and those with large purses. They also involve machinery that vastly extends our skills in making things. If we want to understand the growth of our abilities to make things, we have to understand the development of our tools for doing so. The big dig is a visually and financially remarkable project. Our abilities to make tools capable of working at finer and finer degrees of precision, reliably mounting untold thousands of transistors into smaller and smaller integrated circuits, for example, and now engineering at the "nano-scale," is having and will have a much broader impact. Thing knowledge stands on the shoulders of giants, giant machines. Only at its peril can a materialist epistemology ignore these objective epistemological objects.

10. IS THERE AN "EMPIRICAL BASIS"?

Both theories and instruments express knowledge of aspects of the universe. Knowledge can be expressed in many different ways. Theories express knowledge through the descriptive and argumentative functions of language. Instruments express knowledge both through the representational possibilities that materials offer and through the instrumental functions they deploy. Both should be understood to populate a neo-Popperian world 3.

In some of his more striking passages Popper writes as if objective knowledge, world 3, could exist without human help. He considers the possibility of books of logarithms, produced by computer, distributed to libraries, yet never read. "Yet each of these figures [of logarithms] contains what I call 'objective knowledge'" (Popper 1972, p. 115). In my discussion of functions (§§ *5–6* above), I noted that they connect humans with the world, but I was intentionally vague about the nature and depth of this connection. I focused on a function's making up a phenomenon. Popper's possibility of knowledge entirely disconnected from a knowing subject reappears. Must an artifact be crafted by a human being to count as knowledge? And how clearly must those doing the crafting understand conceptually what they are doing? Jason Saunderson did not know why photomultiplier tube output was sensitive to precisely where light struck the tube's cathode. But he could deal with this mystery without knowing its source. Livingston clearly misunderstood what he was doing in getting his early cyclotron to work. And several of the early uses of photomultiplier tubes relied on a different conceptualization of their function from that of their designers. The "dark current" the tubes produced was, in their designers' view, noise. For others, it was useful in the generation of radar-jamming signals. What about the creations of biological evolution? Do spiderwebs bear knowledge of insect catching? Do naturally occurring phenomena bear knowledge? Does our solar system bear knowledge of gravity?

My distinction between thin and thick notions of function is connected to the distinction between objective and subjective concepts of knowledge. Subjective knowledge is closely tied to subjects and draws on a thick, intention-laden notion of knowledge. As such, it is saddled with the host of problems of intention that I have spelled out at the beginning of section 6. Objective knowledge divorces itself from subjects and requires only a thin notion of function. Popper's minimal criterion is that "in order to belong to the third world of objective knowledge, a book should—in principle, or virtually—be capable of being grasped (or deciphered, or understood, or 'known') by somebody" (Popper 1972, p. 116). Extend such a view to material artifacts and we are led down the path that leads to spiderwebs and solar systems bearing knowledge—knowledge that has never subjectively been embraced by anyone. With the development of black-boxed instrumentation and, more recently, of "expert systems," Popper's logarithmic fantasy becomes more pressing. Recently, a medical expert system was used to gauge the performance of doctors at Massachusetts General Hospital. In 3 percent of cases, doctors' orders were assessed by the expert system to be of no help; in 0.3 percent of cases, they were judged harmful.

Susan Haack, in a series of publications (1979, 1991, 1993), has taken strong issue with Popper's elimination of the knowing subject:

> I agree, of course, that our theories may have unforeseen consequences, that scientific knowledge far exceeds what is known or believed by any individual, that journals, computers, and libraries are vital for the transmission of scientific knowledge, and that the contents of journals, etc., may, for some purposes, be fruitfully studied in their own right. But, unlike Popper, I don't allow scientific knowledge to include "knowledge" *no one* ever has, had, or will have, and I won't allow epistemology to renounce its interest in the cognitive agents who devise, study, learn, transmit, test, and reject scientific theories. (Haack 1979, p. 326; emphasis in original)

Haack presents a series of carefully articulated arguments to show that humans are essential to knowledge, that Popper's talk of the autonomy of world 3 is wrong, confused, or metaphorical at best.

Of her arguments against epistemology without a knowing subject, Haack's most fundamental arguments focus on the empirical basis for putative Popperian world 3 knowledge. At some point, whatever is known must have some kind of empirical justification. Good guesses don't count as knowledge. For Popper, justification lies in critical testing. A theory in world 3 must be capable of being tested against "basic statements" that are taken as stating basic empirical truths. If accepted basic statements contradict predictions (deductions) from a theory, the theory should be abandoned (Popper 1959, [1962] 1969). Where do "basic statements" come from? According to Popper, they are adopted as a result of a kind of decision on the part of the scientific community; they are accepted as a matter of convention. Experience itself does not justify basic statements: “Experiences can motivate a decision, and hence an acceptance or rejection of a statement, but a basic statement cannot be justified by them—no more than by thumping the table” (Popper 1959, p. 105; quoted in Haack 1991, p. 371). Haack finds Popper’s turn to something like “empirical truth by community decision” both surprising, given Popper’s strongly held rationalism, and deeply troubling.

She argues that Popper is forced into this unsatisfactory position regarding the empirical basis for scientific knowledge by his view that nothing beyond strictly deductive arguments serves to underwrite the rationality of science. This fuels both an “anti-inductivist” argument and an “anti-psychologistic” argument against the possibility of justifying basic statements directly by experience. The anti-inductivist argument notes that a basic statement cannot simply report experience. The very terms in which a basic statement is couched already commit it to content well beyond a local empirical report. Noting, for example, that magnesium has a spectral line at 5,167 Å presupposes a load of knowledge about the decomposition of substances into elements, the stability of elemental spectra, and so on. Since such basic statements cannot be justified inductively by experience for Popper, they must instead be accepted “by convention” as according with both accepted theory and experience. The anti-psychologistic argument notes that it would be a category mistake to say that an experience can stand in any kind of logical relationship, let alone a deductive relationship, to a statement. At best, an experience can be psychologically causally related to statements. But for Popper, psychological causes are not rational justifications (Haack 1991, pp. 370–74; 1993, pp. 98–102).

Popper then opts for an epistemology rooted in a world largely divorced from human consciousness. It is a world of propositions that stand in various deductive relations to one another. Humans interact with this world, examining and articulating these propositions and their relations. But, ultimately, the empirical justification for any of the basic propositions in this world of objective knowledge is a matter of conventional choice on the part of the scientific community.

Haack is not the first to take issue with Popper on this point. She herself considers some early versions of this criticism leveled against Popper by Anthony Quinton and A. J. Ayer (Quinton 1966; Ayer 1974). She does not, however, take note of a large literature that, among other things, has concerned itself with Popper’s turn to conventionalism. Imre Lakatos’s essay “Falsification and the Methodology of Scientific Research Programmes” is the first important contribution to this literature (Lakatos 1970). Lakatos abandons truth in favor of the growth of scientific knowledge, what Hacking has called “a surrogate for truth” (Lakatos 1970; Hacking 1983a, ch. 8). But Lakatos characterizes knowledge in purely theoretical terms, leaving little room for advances in experimental or instrumental aspects of science. Work on the philosophy of experiment, starting with Hacking’s 1983 *Representing and Intervening,* has provided a much-needed articulation of the variety of components in the creation of the empirical end of science.

Hacking’s 1992 essay “The Self-Vindication of the Laboratory Sciences” reaches a conclusion that is a wonderfully developed version of Popper’s “conventionalism.” Hacking distinguishes fifteen basic elements in laboratory science. He groups these under three basic headings, ideas, things, and marks. Ideas include questions, background knowledge, systematic theory, topical hypotheses, and models of the apparatus. Things include the target, the source of its modification, detectors, tools, and data generators, and marks include data, data assessment, data reduction, data analysis, and interpretation (Hacking 1992, pp. 44–50). Hacking proposes that laboratory science consists of bringing these fifteen elements into “some kind of consilience” (ibid., p. 58). This is the self-vindication of laboratory science:

> We create apparatus that generates data that confirm theories; we judge apparatus by its ability to produce data that fit. There is little new in this seeming circularity except taking the material world into account. The most succinct statement of the idea, for purely intellectual operations, is Nelson Goodman’s summary (1983 p. 64) of how we “justify” both deduction and induction: “A rule is amended if it yields an inference we are unwilling to accept; an inference is rejected if it violates a rule that we are unwilling to amend.”… The truth is that there is a play between theory and observation, but that is a miserly quartertruth. There is a play between many things: data, theory, experiment, phenomenology, equipment, data processing. (ibid., pp. 54–55)

Popper brought “basic statements” taken to describe the empirical world into agreement with theoretical statements. Hacking proposes a similar kind of epistemology with many more elements.

Andrew Pickering extends the number of elements that must be brought into mutual agreement further (1995). For Pickering, all of the elements of the “cultural front” of science and technology can be “plastic resources” in establishing consilience. These include theoretical, material, natural, social,and intentional dimensions of science and technology. If one is having difficulty doing something, for example, making an instrument work in a certain context, one can change intention and stop trying to get it to work in that context (Pickering 1995, ch. 2).

Our ability to articulate exactly how the scientific community “reaches decisions” concerning what “basic statements” are taken to describe experience has come a long way from Popper’s largely a priori arguments. Indeed, we would not now speak of “basic statements,” but rather of “how experiments end” (Galison 1987). Haack would be right, however, to express concern over the result. We still describe the empirical basis of scientific knowledge as one plastic resource to be molded with other plastic resources to yield a coherent result: “A coherence theory of truth? No, a coherence theory of thought, action, materials and marks,” Hacking says (1992, p. 58).

While I am quite comfortable thinking that much of comfortable thinking that much the roughly propositional content of science and technology (what Hacking calls ideas and marks) is a plastic resource, I am less comfortable with the purported plasticity of (at least some of) the material content of science and technology. Faraday’s electromagnetic motor (see chapter

1) was not a plastic resource, but an empirical anchor in a sea of theoretical confusion. Exactly how we talk about this working knowledge, from the most basic "phenomenological descriptions" to the deepest theoretical explanations, is an arena with considerable room for maneuver. But the phenomenon itself will not go away. It may turn out to be uninteresting and/or unimportant, perhaps, like the pulse glass (see chapter 3). But even that unimportant phenomenon would not go away.

Is this an empirical basis for science? No, but it is a mistake to think of science as a theoretical construction "resting on" an empirical basis. These technological creations, model knowledge, working knowledge, and encapsulated knowledge, are all equally part of scientific and technological knowledge. They interact with theoretical knowledge in numerous ways. They can stand in need of theoretical description and explanation. Usually together with theory, but sometimes alone, they can provide us with an understanding of the world. They can encapsulate theory into their functions. And, appropriately set up, they can render information about the world that speaks to other technological or theoretical creations.

I find Haack's concern about the empirical basis for epistemology without a knowing subject appropriate but incorrectly described. A fully plastic theory of consilience in science will not serve. There are differences between the theoretical resources and the material resources that need recognition. But there is no "basis" for science and technology. There are different modes of engaging the world and of understanding the world. Some of these are theoretical and some material. They interact.

Haack might be concerned with our recognition of thing knowledge. She might ask, "What justifies the conclusion that Faraday's motor is a genuine phenomenon and not a fluke?" While this is a legitimate question, its form suggests semantic ascent, "the conclusion *that*.…" When we treat this contrived part of the material world as a phenomenon, manipulating its parts in various functional ways—perhaps to create Barlow's star or Davenport's motor—we have already incorporated it into our toolbox of working knowledge. We are fallible, however. It could have turned out to be a fluke, not suitable for any further material manipulation, let alone replication. Polywater and N-rays come to mind (Franks 1983; Ashmore 1993). One way of thinking of our material manipulation of some bit of working knowledge is as a test of its stability and reliability. Herein lies empirical justification, but it must not be understood foundationally. All this work is part of making our thought, action, materials, and marks cohere.

11. WORDS, THINGS, AND HISTORY

There is an asymmetry in the "plasticity" of Hacking's things and ideas or marks. Things are less plastic than ideas and marks. Two examples, one from the eighteenth century, another from the twentieth, clarify the point.

James Watt is remembered for his improvements to the steam engine. He also engaged in a bitter priority dispute with Henry Cavendish over who discovered that water is not a simple substance, or element. Watt was up on the chemistry of his day, but much of what he says he is doing makes little sense by today's standards. He believed in a modified phlogiston theory. Despite this outdated way of *talking* about various substances, however, Watt was fully able to do things with these substances. His work on the steam engine harnessed the power of water, which he deployed and developed despite his erroneous theoretical views (see chapter 8 for more detail on this point).

Watt first communicated his discovery that water is not a simple substance in a letter to Joseph Priestley. "Water is composed of dephlogisticated air and phlogiston deprived of part of their latent or elementary heat," Watt writes (quoted in Muirhead 1859, p. 321). Later, in 1783, he wrote to Joseph Banks, the secretary of the Royal Society, with a recipe for making water:

To make Water:

> R. Of pure air and of phlogiston Q. S., or if you wish to be very exact, of pure air one part, of phlogiston, in a fluid form, two parts, by measure. Put them into a strong glass vessel, which admits of being shut quite close; mix them, fire them with the electric spark; they will explode, and throw out their elementary heat. Give that time to escape, and you will find the water, (equal in weight to the air), adhering to the sides of the vessel. Keep it in a phial close corked for use. (quoted in ibid., p. 322)

Watt described what he was doing incorrectly, but we know what reaction he was experimenting with. The "pure air" he writes of is what we now call oxygen. Phlogiston is what we now call hydrogen. Before 1778, phlogiston was supposed to be a substance that, when combined with metallic ore, produced a metal; it was also a substance that humans threw off in respiring. This stuff does not exist. But what we now call hydrogen combines with what we now call oxygen to produce water and has many of the other properties phlogiston was supposed to have had. This was the phlogiston of the "modified phlogiston theory" current in 1785 (Conant and Nash 1957, p. 110). Watt was quite able to manipulate this stuff reliably to make water. However we bring our ideas and marks into consilience with it—in terms of phlogiston and pure air or of hydrogen and oxygen—the phenomenon was reliable. Was then, still is.

Consider a more recent example from the history of artificial intelligence. In his seminal paper "Computing Machinery and Intelligence," Alan Turing seems to say that "computer thought" is the same as human thought if a computer's typewritten linguistic behavior cannot be distinguished from a human's typewritten linguistic behavior: the "Turing test." Questions about the similarity of the internal mental states of humans and the (possible) internal states of computers would thus be answerable on the basis of the external behavior of both kinds of entity. We know that humans have internal mental states, and Turing seems to say that computers have internal mental states too if their external behavior is sufficiently similar to external human behavior. Turing apparently gives us a criterion both for the reality of internal mental states of computers and for the similarity of those states to human mental states.

On the contrary, however, Turing actually rejects the question about the reality of computer thought: "The original question, 'Can machines think?' I believe to be too meaningless to deserve discussion," he says ([1950] 1981, p. 57). However, he further believed that in the near future (for Turing, within fifty years of 1950), it would be possible to construct machines that could *imitate* typewritten human language interaction to such a degree that "an average interrogator will not have more than 70 percent chance" (ibid.) of correctly distinguishing language generated by a computer from that generated by a human being. As a consequence, "the use of words and general educated opinion will have altered so much that one will be able to speak of machines thinking without expecting to be contradicted" (ibid.).

Turing sees the relationship between our talk about computer thought and our interventions with computers historically. With the emergence of a new technology (new ways of doing) comes new ways of speaking; in particular, Turing says, we shall find that it is natural to speak of computer thought. The (predicted) reliable public behavior of computers will result in an alteration in the language with which we talk about computers.

Both of these examples show our ideas being brought into consilience with our interventions in the world. But in both cases, it is our ideas that must accommodate established phenomena (Watt) or hypothesized future phenomena (Turing). Watt was able to produce a reliable phenomenon despite having a theory for the substances and interactions involved that was controversial in his day and that we now regard as wrong. As the ideas attached to these substances and their interactions changed, Watt's phenomenon remained a reliable stable phenomenon, just described differently. It would be astounding if it hadn't stayed stable, for the natural world neither understands nor responds to our descriptions of it. This is a respect in which the natural world is markedly different from the social world.

12. POPPER ON LIBRARIES AND THINGS

Early on in his essay "Epistemology without a Knowing Subject," Popper presents an argument that could seem to shed doubt on the epistemological place of thing knowledge. He has us consider two thought experiments:

> Experiment (1). All our machines and tools are destroyed, and all our subjective learning, including our subjective knowledge of machines and tools, and how to use them. But *libraries and our capacity to learn from them* survive. Clearly, after much suffering, our world may get going again.
>
> Experiment (2). As before,… But this time, all libraries are destroyed also, so that our capacity to learn from books becomes useless.
>
> If you think about these two experiments, the reality, significance, and degree of autonomy of the third world (as well as its effects on the second and first worlds) may perhaps become a little clearer to you. For in the second case there will be no re-emergence of civilization for many millennia. (Popper 1972, pp. 107–8; emphasis in original)

Popper’s argument here is aimed, not at demoting the importance of “machines and tools,” but rather at urging the autonomy of his linguistically based world 3. But the fact that he mentions “machines and tools,” and that their existence, absent libraries, does not support the “reemergence of civilization,” may seem to put their epistemological importance into question.

I have two responses to this argument of Popper’s. First, as with any thought experiment, the conclusion Popper draws from the experiment exposes his conceptual commitments, not “the truth of the matter.” Second, Popper’s experiments are not set up to test for the relative importance of machines and propositions. To do this, we would need to consider an alternative pair of thought experiments, one where the machines and tools are destroyed but the libraries remain intact, and another where the libraries are destroyed but the machines and tools remain intact. I urge a different conclusion—exposing my different conceptual commitments—to this alternative thought experiment.

Popper is optimistic about a civilization that has had its “material infrastructure” destroyed, but that retains libraries and the “capacity to learn from them.” This reveals his commitment to the importance of the written word. Nothing I have to say would question the importance of the written word. Popper certainly is right that the preservation of libraries and our capacity to learn from them is epistemologically very important. But Popper does not consider the importance of tools and machinery and *our capacity to use and learn from them.* Much recent historical work has demonstrated that the written record is not sufficient to allow us to reproduce instruments and machinery. We need to learn from the machinery and from our collective experiences with the machinery. No matter how much we might learn from a library, we would not be able to make a shelter unless we were able to convert natural resources, such as trees, into appropriate components (such as boards) and join those together with appropriate tools (such as a hammer and nails). Furthermore, our ability to make new, *better* machinery and tools depends on previously not-quite-as-good machinery and tools. It is worth considering that in most stories of life after an apocalyptic collapse of civilization, people who can tinker with things are key to progress. If our machinery and tools and our knowledge of how to use them were destroyed, it would indeed be a long time before civilization reemerged.

Popper’s two thought experiments are aimed at showing the autonomy of his world 3. Were he to consider thought experiments aimed at demonstrating the relative epistemological merits of book knowledge as opposed to material knowledge, he would have come up with two thought experiments such as these:

Experiment 1: All our machines, tools and all our abilities to make things in the material world are destroyed. All our subjective knowledge of machines and tools (and everything else) is lost. But libraries and our capacity to learn from them survive.

Experiment 2: All our libraries and our capacity to learn from the written word are destroyed. But our tools and machines remain, as do our abilities to use and manipulate them.

These thought experiments are much more difficult to read morals from. Indeed, it is difficult to imagine the two scenarios, given the degree to which literary and material modes of knowing interpenetrate each other; in this sense, both may be inconsistent. Both represent drastic losses.

But were I to choose, I would guess that civilization of a sort would emerge more quickly in the second case. Experiment 1 is something akin to the state of most nonhuman animals, with the added ability to read (and write, I suppose). Most nonhuman animals live in a world that is not, as the human world is, overwhelmingly populated by things of their making, a "technosphere." Yes, there is some primitive tool use, yes, birds make nests and beavers make dams. But for most nonhuman animals, most of their world is not a world of their conscious design and making. Were humans to lose our technosphere and our abilities to make things, we would be put in the position of these animals, with the added ability to read books in libraries. Could these books teach us how to make things? That depends on the degree to which this ability has been lost. If we lost our "hand-eye" coordination, I think it would be a very long time before we created anything remotely like our current civilization.

Experiment 2 is something akin to the state of many people today, according to studies of world literacy, and if one goes back in time a few hundred years, it is akin to the state of most people in "advanced societies." Widespread literacy is a relatively modern development. Again, depending on the degree to which our abilities to read and write were destroyed, it would be a long time before civilization was restored. All of our political, legal, and commercial structures would have to be recreated. If we did not have the ability to read and write because of some kind of universal brain damage, this would take a very long time. If we had these abilities, but had lost our libraries, then much would depend on human memory and determination to reestablish these structures. My guess, however, is that it would come faster than in experiment 1.

13. THE METAPHYSICS OF THING KNOWLEDGE

I close with the ontological problem thing knowledge poses. Popper's world 3 is not a domain of things. For Popper, our material creations are world 1 applications of world 3 theories: "It cannot seriously be denied that the third world of mathematical and scientific theories exerts an immense influence upon the first world. It does so, for instance, through the intervention of technologists who effect changes in the first world by applying certain consequences of these theories" (Popper 1972, p. 155).

Viewing the fruits of technology as applications or instantiations of theoretical knowledge will not stand historical scrutiny. Faraday's motor was not an instantiation of his theory of electromagnetism. But the alternative is perplexing. It would seem that including such world 1 objects in Popper's world 3 produces ontological confusion. One would like to know what difference there is, if any, between my world 1/world 3 objects and regular world 1 objects.

The first thing to realize is that theories themselves require material expression. Popper himself speaks at length of libraries being the repositories of world 3. Anyone who has moved even a small collection of books knows that they are distressingly material! Popper also writes of “paper and pencil operations” in the solution of problems (e.g., the product of 777 and 111) (1972, p. 168). Paper and pencil operations are operations in the material world. Of course, Popper might say that these operations are linguistic items with world 3 meaning, what he calls “third-world structural units.” They are “capable of being grasped (or deciphered, or understood, or ‘known’)” (ibid., p. 116). With instruments, tools and other material products of human ingenuity, it is not quite the same. They don’t have meaning in the same sense that propositions do. Yet it is possible to grasp “a meaning” of a material object. Davenport did so with Henry’s electromagnet; Maurice Wilkins and Rosalind Franklin did so when they saw Watson and Crick’s model of DNA.

So the question remains. What distinguishes a part of world 1 that is also a part of world 3 from that which is not? What are the differences between a riverbed, a spiderweb, and the things I call thing knowledge?

First of all, I insist on these differences. Whatever the analysis of them, we can distinguish objects of human manufacture—both linguistic and material—from other natural products of life. Both can be distinguished from the products of purely physical forces. A moonscape differs from a landscape, which in turn differs from a painting of a landscape. What an art historian writes about a landscape is different yet again.[7]

Second, I recall one of Hacking’s observations about phenomena: naturally occurring phenomena are rare. Before one protests that phenomena are ubiquitous—“phenomenon. 1. An occurrence, a circumstance, or a fact that is perceptible by the senses” *(American Heritage College Dictionary,* 3d ed., s.v.)—let me clarify. Hacking follows an established usage in the sciences: “A phenomenon is noteworthy. A phenomenon is discernible. A phenomenon is commonly an event or process of a certain type that occurs regularly under definite circumstances.… A phenomenon, for me, is something public, regular, possibly law-like, but perhaps exceptional” (Hacking 1983a, pp. 221–22). He is at pains to dissociate his use of the word from other usages where “phenomena” denotes the nearly constant ebb and flow of sensual appearances: “My use of the word ‘phenomenon’ is like that of the physicists. It must be kept as separate as possible from the philosophers’ phenomenalism, phenomenology and private, fleeting, sensedata” (ibid., p. 222). Hacking’s use of “phenomenon” allows him to draw a distinction between what William James called the “blooming, buzzing confusion” (James [1890] 1955, 1: 488) that presents itself to our senses and the ordered regularities that are the bread and butter of the natural sciences. Following James here, Hacking writes: “In nature there is just complexity, which we are remarkably able to analyze. We do so by distinguishing, in the mind, numerous different laws. We also do so, by presenting, in the laboratory, pure, isolated phenomena” (ibid., p. 226). Beyond these manufactured—pure, isolated phenomena—naturally occurring phenomena are rare: “Outside of the planets and stars and tides there are few enough phenomena in nature, waiting to be observed…. Every time I say that there are only so many phenomena out there in nature to be observed—60 say—

someone wisely reminds me that there are some more. But even those who construct the longest lists will agree that most of the phenomena of modern physics are manufactured…. [T]he Faraday effect, the Hall effect, the Josephson effect—are the keys that unlock the universe. People made the keys—and perhaps the locks in which they turn" (ibid., pp. 227–28). The "expressivity" of instruments—how they are part of both world 3 and world 1—is a consequence of their making up such Hackingesque phenomena, what I call "working knowledge."

It is significant that both Hacking and Popper waffle on biological phenomena. Popper sees many biological products as akin to theories: "The tentative solutions which animals and plants incorporate into their anatomy and their behavior are biological analogs of theories" (Popper 1972, p. 145). Yet he does not include them in his world 3. Hacking writes, "Each species of plant and animal has its habits; I suppose each of those is a phenomenon. Perhaps natural history is as full of phenomena as the skies of night" (Hacking 1983a, p. 227). Yet earlier, he writes:

> It will be protested that the world is full of manifest phenomena. All sorts of pastoral remarks will be recalled. Yet these are chiefly mentioned by city-dwelling philosophers who have never reaped corn nor milked a goat in their lives. (Many of my reflections on the world's lack of phenomena derive from the early morning milkstand conversations with our goat, Medea. Years of daily study have failed to reveal any true generalization about Medea, except maybe, "She's ornery often.") (ibid., p. 227)

Hacking's and Popper's ambivalence about the putative phenomena of natural history suggests a further distinction. Thing knowledge, existing in a more refined, constructed space, exhibits greater simplicity—although perhaps less robustness—than do the adaptive living creations of natural history. Perhaps more important, our material creations, through our various acts of calibration, connecting them with one another and with what we say, have a greater depth of justification than do animal phenomena. Spiderwebs are well adapted to catch flies. But there is no connection established between this approach to catching spider food and other possible and actual approaches. We can and do connect direct-reading spectrometers with other spectrographs and with wet chemical techniques.

In the end, then, we have a material realm of thing knowledge, fallible and dynamic like Popper's world 3. A realm with objects we can think about and intervene in to change our physical surroundings—a realm that interacts with worlds 2 and 1. This is a realm where we encapsulate different kinds of knowledge—theoretical, skillful, tacit, and material—into statements, performances, and material bearers of knowledge. It is a material realm that is simultaneously an epistemological realm.