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# Paradigms and Paraphernalia: On the Relationship of Theory and Technology in Science

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# Paradigms and Paraphernalia: On the Relationship of Theory and Technology in Science

**Abstract**
What is the connection between theory and technology in science? What is the relationship between the various activities of "doing" science and the instruments that enable these activities? My interest here is to explore these questions in a very broad and elementary way, occasionally citing examples plucked from the history of science. [*excerpt*]

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# Paradigms and Paraphernalia:

## On the Relation Between Theory and Technology in Science

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*...not only are good experiments based on theory,*
*but even the means to perform them are theory incarnate.*
-- A. Koyr"

What is the connection between theory and technology in science? What is the relationship between the various activities of "doing" science and the instruments that enable these acti- vities? My interest here is to explore these questions in a very broad and elementary way, occasionally citing examples plucked from the history of science.

Perhaps it seems that I am in pursuit of the obvious. Who would doubt that there is a strong tie between scientific theory and technology? The relationship is reciprocal: scientific discoveries often yield technological advances, and new technology permits further discoveries. Although this account is accurate, it is superficial. My analysis of the relationship will lead me to advance a strong claim. I believe that theory and technology are so intertwined in science that neither can be studied indepen- dently of the other without distortion and diminishment of understanding. Ultimately, I want to argue that a deeper under- standing of this relationship is essential to an adequate philosop- hy of science and to science education.

### The Technology of Discovery

Science is an enterprise that requires paraphernalia. The image of the scientist presented in the movies and other media of popular culture is that of the researcher in a laboratory or in the field surrounded by scientific paraphernalia. Faust in his study. Dr. Frankenstein in his laboratory. The heroic scientists of so many science fiction films. It is the apparatus and materials that surround them -- the microscopes, retorts, Bunsen burners, oscilloscopes, Geiger counters, electromagnets (often arranged in amusingly nonfunctional arrays) -- all the stuff that says "science is being done here."

Of course the instruments have changed with the ages -- the era of simple weights and measures; the era of optical telescopes and pendulum clocks; the era of Leyden jars and lightning rods; and now the era of radiotelescopes and gigantic scintillation counters. The pursuit of science requires more sophisticated and more expensive equipment with each passing year. Sadly, the days of "table top science" seem gone forever.

To begin to analyze the role of these devices, one must begin with some basic distinctions, because not all the paraphernalia one is likely to find in a research center have the same relationship to the pursuit of science. Taking inventory of the contents of a laboratory, one might find *scientific objects* -- the specimens, substances, and artifacts selected for study by the scientists. One might also find *supplies* -- computer disks, solvents, photographic plates, food for laboratory animals. There may be *equipment* that is only indirectly related to the ongoing research -- for example, animal cages, high intensity lamps, exhaust fans, protective glasses, and so on. Finally, one may locate the devices that are of central interest here, the *scientific instruments* -- the galvanometers, spectrophotometers, cloud chambers, mass spectrometers, and so on (some of them much too large to be portable -- for example, electron microscopes, superconducting supercolliders, and radiotelescopes).[1]

Such scientific instruments may function in several ways. They extend our senses. They detect the presence of a phenomenon. They weigh, count, measure, or otherwise assess some dimension of a phenomenon. They may record these observations. They may use data to construct a representation or image of a phenomenon. Some simple instruments do only one of these things; other instruments combine operations. Some instruments alter one or more properties of a phenomenon in predetermined and measurable ways. In all causes, they provide purposefully mediated contact between the researcher and Nature.

These devices represent ingenious combinations of our knowledge of the world and our "know how." The development of high powered optical telescopes, for example, requires not only a knowledge of optics but also sophisticated processes of lens grinding and the preparation of special materials. This is the conventional picture: scientific knowledge grows; it is applied by ingenious inventors often aided by serendipity and engineers to create new technology; this technology is then used in scientific research to extend our knowledge. In research, instruments are used to confirm or refute a theory or hypothesis. The introduction of instruments into research reflects the empiricism of science, as they transform the unobservable into the sensory data of meters, graphs, indicators, gauges, etc. Instruments seem neutral and impersonal. They provide observations devoid of researcher prejudice. The data provided are objectified: "It's right there on the film!" "We've recorded a significant fluctuation; look here at the meter." "No doubt you've gained material: look at the scales." Often scientific instruments violate researcher expectations or carry the experimenter far beyond current knowledge or purpose. One thinks of Galileo, Leeuwenhoek, and Rontgen as observers who were astonished by the phenomena revealed by their instruments. Occasionally, instruments may advance our knowledge by their **failure** to detect a phenomenon. One thinks of Michelson and Morley failing to detect the ether wind.

On this simplistic view, then, scientific instruments seem logically independent of scientific theory and the commitments of the experimenter -- indeed, their effectiveness in experiments seems in large part to rest on that independence. The levels of theory and observation are thought to be quite distinct. The relationship appears only a matter of the practical relevance to the phenomena under study. The theory, the technology, and the observer are each in its own place and isolable from the others.

However, as soon as this account is given, potentially significant qualifications and reservations must be admitted. First, for an instrument to function properly, it must be *in good working order.* Determining whether a given instrument is in good working order requires a diagnostic routine that is independent of the instrument's immediate application. For example, suppose a technician applies a Geiger counter to a substance and receives a reading of intense radioactivity. The technician may doubt whether the Geiger counter is in good working order. To test it, the technician may apply it to other substances of known levels of radioactivity for comparison -- levels known to the technician. Or some other independent diagnostic test will be applied. Secondly, instruments must be properly calibrated. Calibration is a complex technical problem that requires the application of independent standards, i.e., a comparison with known and certified values. In practice, portable standards are applied for comparison to permit instrument adjustment.

Third, instruments function properly only within a range of application, and, fourth, they assume that certain standard conditions obtain. A scale may, for example, give accurate readings for weights of a certain range only -- say, from one gram to ten pounds. Objects with less weight or more weight will not be read accurately, if at all, and a very heavy object may damage the instrument. In addition, this scale may assume the gravita- tional pull of Earth at sea level. Fifth, instruments come with a set of instructions; that is, they have established protocols for their proper use. A device can be in proper working order, accurately calibrated, applied within the proper range of phenomena under standard conditions, and still be dysfunctional if the technician is using the machine improperly. Sixth, many instru- ments require observer competence. This means that skill and experience are required to interpret the data provided by the instrument. Reading a sonogram or an electroencephalogram, for example, requires interpretive skill. Only some observers are competent observers, and the certification of this competence is a knotty epistemological problem.

Undeniably, the instruments of science do provide a kind of objectivity that occasionally yields findings surprising to the researcher. But the six factors outlined above reveal ways in which the researcher's knowledge, commitments, and skills are implicated in the instruments and their proper functioning. When we design our technology of discovery we reveal what we expect to find with it.

## Instruments and Human Purpose

"Paraphernalia" is a broad concept. It includes a wide array of devices, including tools, utensils, implements, equipment, machines, appliances, engines, apparatus, and instruments. And all of these are imbued with human purpose.

In such works as *Personal Knowledge* and *The Study of Man*, Michael Polanyi discussed the nature of machines. He pointed out that "a knowledge of physics and chemistry would in itself not enable us to recognize a machine" (Polanyi 1958,1964, p. 330). We could produce a complete physico-chemical analysis of the object and still have no sense of whether it is a machine or, let's say, a sculpture. If we were told it was a machine, we might still have no surmise as to its use, and we would certainly have no way to derive its operational status and use from our knowledge of physics and chemistry. We would not know what it was for and whether it was operational. How could we make this determination? To quote Polanyi, *"only by testing the object practically as a possible instance of known, or conceivable, machines"* can we learn whether the thing serves any purpose and, if so, what purpose (Polanyi, p. 330). That is a fairly ponderous, open-ended test, though it is probably an accurate description of what we would do if, for example, when browsing in an antique shop, we came upon an implement we could not identify. Or what space explorers might do upon finding a suspiciously artificial alien object. "What is this device? What could it be used for?

In these situations, we cannot make a definitive determination because we lack an important piece of knowledge: knowledge of intended purpose. That insight becomes fundamental in Polanyi's account: to understand a machine is to enter the realm of purpose. Let me quote him at length:

> For a machine is a machine only for someone who relies on it (actually or hypothetically) for some purpose, that he believes to be attainable by what he considers to be the proper functioning of the machine: it is the instrument of the person who relies on it . . .
>
> Since the control exercised over the machine by the user's mind is -- like all interpretations of a system of strict rules -- necessarily unspecifiable, the machine can be said to function intelligently only by aid of unspecifiable personal coefficients supplied by the user's mind. (Polanyi, p. 262)

According to Polanyi, a machine (for example, a typewriter, an engine, a telephone, or a camera) is characterized by an operational principle. Such a principle is formulable for a patent, which specifies just how the "characteristic parts" work together to achieve the machine's purpose. Such an operational principle extends the conception of the machine to include hypothe- tical objects of varying sizes, made of a wide range of materials. The range of things which might be the instances of such an operational principle, the individual objects which might be machines of the same kind, is not specifiable by pure science.

The operational principles define a machine "in good working order." This means that they explain the proper and efficient functioning of the machine. They cannot, however, explain why a machine is "out of order." For an explanation of a particular equipment failure we must turn to science -- to physics and chemistry. "The operational principles of machines are therefore *rules of rightness*, which account only for the successful working of machines but leave their failures entirely unexplained" (Polany- i, p. 329).

Like a machine, an instrument is a device designed to achieve an end. Instruments, like machines, have operational principles. However, the term "instrument" suggests a device of delicate construction, or of a precision or capability which extends beyond normal mechanical or manual operation. These connotations hint at the close ties between instrument design and scientific theory.

Many times instruments have been designed for specific research needs. In *The Structure of Scientific Revolutions*, Thomas S. Kuhn lists several examples:

> Special telescopes to demonstrate the Copernican prediction of annual parallax; Atwood's machine, first invented almost a century after the *Principia*, to give the first unequivocal demonstration of Newton's second law; Foucault's apparatus to show that the speed of light is greater in air than in water; or the gigantic scintil- lation counter designed to demonstrate the existence of the neutrino -- these pieces of special apparatus and many others like them illustrate the immense effort and ingenuity that have been required to bring nature and theory into closer and closer agreement. (Kuhn 1962, 1970, p. 26)

In some cases, scientific theory has predicted a result years before an instrument could be designed to provide empirical confirmation. Once available and useful in experiments, a piece of technology can come to shape the research agenda.

## Paradigms and Paraphernalia

The brilliant and influential account of science outlined by Thomas Kuhn in *The Structure of Scientific Revolutions* provides deeper insights into the relation between scientific knowledge and scientific instruments. His central concept -- the paradigm -- makes impossible a clean separation between theory and observation. "The instance of the paradigm sets the problem to be solved; often the paradigm theory is implicated directly in the design of apparatus able to solve the problem" (Kuhn, p. 27). Kuhn notes that Newton's *Principia* established a paradigm expressed in laws; however, Newton's second law was at the time unconfirmed by empirical observation. Nearly a century later, Atwood invented his machine to give "the first unequivocal demonstration" of Newton's second law. "Without the *Principia* . . . measurements made with the Atwood machine would have meant nothing at all" (Kuhn, p. 27). Instruments sometimes detect paradigmatic anomalies, and they may therefore be essential to the conceptual revolution that replaces one paradigm with another. RÖntgen's cathode ray tube produced radiation so unanticipated and unknown it was labeled "X-rays," and it launched a new paradigm.

Some instruments survive the revolution -- although their data may be reinterpreted or their ranges of application may be redefin- ed. The revolution from Newtonian to Einsteinian physics, for example, left many instruments of physics intact. Occasionally, the instrument itself is completely revisioned. Consider this example from Kuhn:

> the assimilation of Franklin's paradigm, the electrician looking at a Leyden jar saw something different from what he had seen before. The device had become a condenser, for which neither the jar shape nor glass was required. Instead, the two conducting coatings -- one of which had been no part of the original device - - emerged to prominence (Kuhn, p. 117).

Occasionally, some instruments do not survive the revolution and are cast aside.

Instruments are theory-laden artifacts, inexplicable without reference to the theory embedded in their design and operational elements. Consider the Wilson cloud chamber. What is necessary to understand this apparatus? Polanyi would note that, until we understand the purpose for which it is designed, we cannot tell whether it is a machine and, if so, whether it is functioning properly. In this case, however, the purpose of the machine cannot be stated without reference to the content of scientific theory. As you know, a Wilson cloud chamber produces a very moist cloud prevented from condensation by the absence of dust. The cloud reveals the presence of energetic particles passing through the chamber when tiny droplets of water form around the ions produced along the route the particle travels. When the cloud is placed within a magnetic field, information about the mass and charge of the particle may be revealed by its path. The conception of this device rests on the putative existence of unobservable entities postulated in sub-atomic theory. Of course, no observer can see the particle -- only the tracks left in the cloud. Such an apparatus is theory incarnate.

## Conclusion

I have provided nothing so splendid as a linear argument. But this cluster of comments, observations, and examples do have a cumulative effect. While scientific instruments are sufficiently independent to present anomalies and refute dearly held hypotheses, they are also linked to theory. First, there are the profound ties of any machine to human purpose. Second, there are the six elements in the effective use of an instrument: (1) good working order; (2) accurate calibration; (3) range of application; (4) standard conditions; (5) protocols of use; and (6) a competent observer. These all display linkages between our knowledge and commitments and the operation of the instrument. Third, there is the deliberate design of instruments to meet a research agenda, incorporating the application of theoretical content. Finally, there is the image of instruments as theory-laden artifacts of our paradigms.

If the relationship between theory and technology in science is accurately described here, it deserves a more central place in the philosophy of science and in science education. There is significant work to be done clarifying the variety of relationships that begin from the vision of an instrument as an embodied theory. Seeing our paradigms in our paraphernalia, and vice-versa, may give us an enriched understanding of both.

## NOTES

1 Some instruments, such as a laser, may be ancillary equipment in one instance of research (when, e.g., used in surgery) and a central scientific instrument in another project (in which the effects or applicability of lasers are researched, e.g.).

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