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The Journal of Mind and Behavior
Winter 1996, Volume 17, Number 1
Pages 21–30
ISSN 0271–0137

Instrument Driven Theory

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Instruments are used primarily to provide data for testing theoretical predictions. However, sometimes instrument development sets the occasion for profound theoretical changes which are totally unanticipated. This article presents examples of instrument driven theory derived from biology and physics (astronomy) as well as discussing implications for psychology. The role of theory in the design of instruments is considered.

"Normal science" (cf. Kuhn, 1970) is characterized by progressive knowledge gains governed by a theoretical orientation called a paradigm. In this context, instruments yield measurements which are used to help choose among existing hypotheses. Instruments thereby function mainly as tools in the service of theory testing.

Occasionally, science progresses by making a qualitative leap. The most widely discussed instances of such extraordinary changes are theory based. Theoretical advances provide a new perspective which is empirically supported by subsequent measurements. The purpose of this article is to call attention to another method by which scientific progress takes a qualitative leap. I refer to instances where new instruments enable radical changes in theory that would probably not have otherwise occurred. Although only one instance of instrument driven theory is required to establish the validity of my thesis, several supporting examples are presented to show that instances of instrument driven theory are not rare events. No attempt has been made to exhaustively document instances of instrument driven theory nor is it implied that the examples presented below are necessarily the most important. Nor has an attempt been made to evaluate the extent to which such instances occur or to compare their frequency with more numerous instances

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where measurement helps refine, rather than create, theory. The main point remains that instruments sometimes provide a radical new perspective which sets the occasion for qualitative changes in theory. Instrument development is therefore an important avenue of theoretical progress.

Biology

Prior to the microscope, biology considered only those life forms that could be seen with the naked eye. No formal theory of an ultra small world existed to motivate the development of an instrument to test such a hypothesis. Nor did the microscope result from any known informal biologically pertinent theory. Since, as Boorstin (1983, p. 327) documents, the exact inventor of the microscope is unknown, the role of theory in the development of the microscope is somewhat difficult to determine.

Partly at issue here is how fully formal knowledge must be organized before the term theory is used to describe it. I object to labeling every informal hunch and expectation as "theory" because that equates a theoretical system such as Einstein's general relativity with a shopper's expectation that cereal is to be found in aisle two. Asserting that the former is formal theory and the latter informal theory is unsatisfactory because it permits all forms of cognition to be so termed as to render the distinction meaningless. Concepts must have negative as well as positive instances if they are to be meaningful.

No evidence exists that the microscope was invented as the result of "optical theory" or that it was developed to test theoretical expectations. For example, one might think that the inventor intended to see small things when constructing the microscope, yet on the other hand, we know that no intention to see distant objects drove the invention of the telescope (see below).

We do know that Antoni van Leeuwenhoek was among the first to systematically use a microscope and is of course associated with its origin. He apparently began his illustrious career in microscopy without theoretical orientation as to what he might find. Boorstin indicates that Leeuwenhoek began simply by looking at one specimen and then another. By examining a drop of water he discovered a world of micro-organisms that had not previously been recorded. Similarly, he made seminal discoveries in microbiology, embryology, histology, botany, and crystallography without the aid of formal theory.

Some of Leeuwenhoek's observations disproved existing theory. Boorstin (1983, p. 332) states, for example, that the existing theory of reproduction held that semen provided fertilizing vapors. When Leeuwenhoek's microscopic studies revealed spermatozoa, the vapor theory was replaced by a concept of male gametes — entities which had not been previously posited. A completely new theoretical idea of a male gamete was enabled by the microscope and would not have arisen without it.

Robert Hooke (1635–1703) did not first theorize about the cellular basis of life and then use a microscope to test the hypothesis. Rather, he examined a thin slice of cork under the microscope, probably because cork was a conveniently available specimen, and then described the cellular structure he observed. The idea that life was based on cells did not exist prior to seeing cells through a microscope.

The history of "clinical diagnosis by laboratory methods" (cf. Davidsohn and Henry, 1974) repeatedly reveals that theoretical reconceptions of disease were driven by analyzing specimens from normal and diseased persons using instruments found in natural science laboratories. Correlations were found between laboratory measurements and clinical status and then diagnostic criteria were developed to separate diseased from normal persons in terms of those measurements. For example, the clinical manifestations of anemia include, but are not limited to, pallor of the skin and mucous membranes, shortness of breath, heart palpitations, and fatigue. Laboratory analysis of the blood indicates that this multidimensional symptom cluster derives from a deficiency of oxygen-carrying substance in the blood; e.g., less than 13.5 grams of hemoglobin per decaliter (gm/dl) in adult males and 12.0 gm/dl for adult females (Davidsohn and Henry, 1974, p. 181). We now diagnose anemia by obtaining a blood specimen, measuring the grams of hemoglobin per decaliter, and comparing the result to normative values. Other disorders, such as hypertension, are defined entirely by the instruments used to document that the disorder exists. Hypo- and hyper-tension are distinguished from normal blood pressure in terms of sphygmomanometer readings. Even the unit of measure has become part of the disease terminology, as when we refer to blood pressure in millimeters of mercury (mm Hg).

Physics/Astronomy

Telescope

Harwit (1981) describes the history of observational discovery in astronomy. Of the seven properties he finds characteristic of astronomical discoveries, the first property concerns the role of new instruments. The new ideas made possible by instruments are almost always unanticipated by existing theory. Qualitative theoretical advances are enabled by the new perspective that the instrument provides. Subsequently, the new instrument is used interactively with the new theoretical insights.

The necessity of theory to the development of scientific instruments is described by Boorstin (1983, p. 314): a Dutch spectacle-maker named Lipperhey observed that children playing in his shop were able to enlarge a distant weather vane by properly spacing selected lenses. Understanding the importance of this observation, he constructed the first telescope. Lipperhey was observant but not yet engaged in hypothesis testing nor was he even aware of the possibility that lenses could be used in combination to better see distant objects.

Telescopes of unknown power were first sold in Paris in 1609 (p. 315). By the end of 1609 Galileo had constructed his own 30 power telescope (p. 318). This device increased the number of visible stars by a factor of 10; the universe was much larger than had been thought. The moon was found to have a rough and uneven surface rather than the smooth polished surface as held by existing theory (p. 320). The centuries-old debate concerning the substance of the Milky Way was resolved as it was seen to be a mass of stars (p. 320). Saturn was seen to have an oval rather than the theoretically-expected circular shape (p. 321). Venus was seen to pass through phases like the moon; that observation eventually fostered the Copernican model of our solar system (p. 321). These theoretical changes resulted because the telescope expanded visual capacity and provided a new perspective that set the occasion for profound theoretical changes that would never have happened in its absence.

Prisms

The composite nature of white light was completely unanticipated until Newton in 1664 passed a light through a round hole and a glass prism onto a screen. There is no evidence that Newton constructed his apparatus to test a formal theory of light. Systematic curiosity was undoubtedly involved. The observational evidence provided by this new instrument was unanticipated. Instead, it advanced our spectral understanding of "white" light. It is unlikely that our current theoretical understanding of light would have developed in the absence of such an instrument.

In 1800, W. Herschel measured the temperature associated with each of the spectral colors from sunlight and reported that the largest value was found beyond the color red. He did not first hypothesize the concept of "infrared" and then construct the apparatus to test that hypothesis. Rather, he was using one instrument, a thermometer, in conjunction with another instrument, the prism, to determine the temperature of colored light. Taking the temperature of a portion of the spectrum invisible to the naked eye led to the discovery that the visible spectrum extended into the infrared. It then became clear that vision revealed only a part of a much larger radiation spectrum — still under active investigation today as evidenced by gamma-ray telescopes. It could then be reasoned that if light contained components extending beyond the red end of the spectrum, perhaps additional components could be found beyond the other, violet end of the spectrum. In 1801

J.W. Ritter reported that light beyond the violet end of the spectrum effected silver salts — thereby discovering ultra-violet radiation.

In 1814 Joseph von Fraunhofer created a new device. He substituted a slit for Newton's hole and used a telescope to gather distant light. No theory has been documented for the slit modification. However, the slit revealed sunlight as a band of spectral colors containing many dark lines. The presence of these dark lines was completely unexpected. No formal or informal theory indicated that changing the hole to a slit would reveal spectral lines; yet this alteration of Newton's apparatus is needed to see them. That spectral lines were not part of any formal or informal theory means that Fraunhofer did not construct this device to determine if spectral lines existed. By the end of his career, he mapped 576 dark lines and demonstrated that their relative positions are constant.

The discovery of spectral lines in sunlight suggested that they might also be found in other light sources. By 1859, Gustav Robert Kirchhoff had connected the observation of bright lines in the spectra of flames with dark lines in the solar spectrum thereby generating a general law of spectral absorption and emission whereby each atom has a unique and characteristic spectrum. In 1861, Kirchhoff and Bunsen compared the solar spectrum with spectra from the flame or spark of the purest available elements thereby establishing the field of spectrochemical analysis which opened up the possibility of analyzing the chemical composition of celestial bodies. They also discovered the elements cesium and rubidium, neither of which was anticipated by theory. In 1901 Johannes Hartmann's high resolution spectral analyses of a nova that occurred in the constellation Perseus resulted in the location of calcium in interstellar space, where no theory predicted any element, let alone a biologically relevant one (see Harwit, 1981, p. 96). These examples demonstrate how certain topics in exobiology were initiated by instrumentation rather than theorization.

Radiation

All planets were long thought to be inert, but in 1955 Bernard Burke and Kenneth Franklin unexpectedly detected radio waves from Jupiter (Harwit, 1981, p. 38). In 1967 Anthony Hewish and Jocelyn Bell made high speed measurements of radio waves and discovered the first pulsar. An entirely new type of astronomical body was thereby presented for theoretical analysis.

The atmosphere transmits infrared radiation with a 2 micron wavelength but does not emit it. Hence, Robert Leighton and Gerry Neugebauer constructed an instrument to survey the sky at this wavelength. No specific hypotheses had been formulated. Nor was the apparatus constructed to test predictions. Rather, Leighton and Neugebauer understood that they possessed a new means to view the heavens and used it systematically. By 1969 their search revealed more than 5,000 infrared emitting stars. Harwit (1981, p. 108) maintains that "Before the start of their systematic search, there was no way of knowing what kind of new source, if any, Leighton and Neugebauer were likely to find." Theory did not guide these discoveries except insofar as one admits, as informal theory, that successful prior experience with instrumentation caused the expectation that new instruments would reveal important new discoveries. Nothing like a formal hypothetico–deductive system was involved.

Astronomers measure the brightness of astronomical bodies on a scale ranging from bright objects with negative numbers to faint objects with positive numbers. Each change of one magnitude alters brightness by a factor of 2.512 so that five orders of magnitude correspond to a 100 fold change in brightness; e.g., $2.512^5 = 100$. The sun, as viewed from earth, measures –26.8. Sirus measures –1.4 and the faintest star visible to the naked eye measures +6. Flamsteed (1991) reports that no astronomical survey of the sky went deeper than +18 until J. Anthony Tyson pointed his CCD (Charged Coupled Device) instrument to areas of the night sky that appeared dark and empty to both naked eye and optical telescope — he thereby revealed the presence of billions of additional stars.

X-rays

Farmelo's (1995) account of Röntgen's discovery of X-rays clearly illustrates the primary formative role of instrumentation with theory entering only after the fact to explain what had been discovered through instrumentation. Röntgen accidentally discovered X-rays while studying streams of electrons called cathode rays. The first theories of X-rays did not emerge until several months after Röntgen's discovery and therefore could not have been used to guide his inquiry. Röntgen received the first Nobel Prize in physics in 1901 for his instrument-based X-ray discovery. This scientific advance was considered so important that Röntgen prevailed in an extremely distinguished field; eight of the other eleven nominees subsequently won Nobel Prizes.

In a recent interview, Hively (1995) describes efforts by Charles Rhodes to invent an X-ray laser. One motivation for creating such a device is to take holographic 3-D pictures of structures as small as one billionth of a meter. The minimal role played by theory is evidenced by Rhodes's comment: "You wouldn't worry about what you'd look at initially, you'd just look, and you'd see something new" (p. 72). Hively comments that "He [Rhodes] had been groping toward an X-ray laser for more than a decade by following his instincts, relying in equal portions on experiment, hard-nosed analysis, and luck, with theory almost an afterthought" (p. 73). Hively further recounts that Rhodes sometimes conducted experiments that a theory-guided investigator would never have performed because no useful results were predicted. Hively reports that Rhodes believed that "According to mainstream physics, xenon clusters shouldn't emit any more X-rays than individual xenon atoms should. The theory behind this conclusion is ensconced in thick reference books containing data compiled over decades of research. 'It's pretty well understood by now,' growls Rhodes. Nonetheless, he thought the theory might be wrong" (p. 73). Rhodes's rebellion against accepted theory was not initially based on a contrary theory but rather on an informal hunch and on a willingness to experiment with his instruments regardless of the predicted result. Armon McPherson, Rhodes's assistant, respects theory even less than does Rhodes but is said ". . . to have a knack for making things work" (p. 73). He utilized laboratory equipment in ways that even Rhodes doubted would be productive but achieved spectacular results. Hively comments [that] "According to everything they [Rhodes and McPherson] both knew about physics, the film should have been almost perfectly clear, yet here was McPherson holding up a piece of film black from exposure to X-rays. Clearly says Rhodes, the xenon clusters floating in this vapor were radiating 'one *devil* of a lot stronger than they should have been.' They had popped off like X-ray supernovas." Rhodes concluded "there was something fundamentally new here" (p. 73). Experimental physicists had provided theoretical physicists with a new phenomenon to explain.

Implications

Conceptual

Scientific knowledge is not always acquired by first theorizing and then testing hypotheses with an instrument or other measuring device. Important new scientific understanding has been, and continues to be, instrument driven. Whereas most accounts of scientific breakthroughs are attributed to new theoretical insights, we have seen that important conceptual shifts sometimes result from the development of a new instrument and may even require an investigator to ignore theory. Examples of instrument driven theory are not infrequent and perhaps are no less numerous than equally rare instances where new theory radically alters research and scientific understanding. While respect for the importance of theory should be retained, equivalent status should be granted to the development of new instruments and/or systematical use of novel apparatuses to gather new data.

Instruments can alter theoretical understanding in other ways. For example, a major difference between modern medicine and its predecessor is that modern medicine understands disease in terms of measurements and analyses conducted in natural science laboratories. Medical theorizing about what normal function entails and the deviations from the norm that constitute "disease" are grounded in the methods and results obtained by using instruments. Microscopic examination of blood reveals red cells; chemical analysis reveals hemoglobin capable of carrying oxygen, which leads to a new understanding of anemia as insufficient hemoglobin. This understanding of disease is dependent upon the results of instruments used to reach the conclusion. The operating characteristics of these instruments shaped the final view of anemia as much as did a priori theory. The case of hypertension further illustrates this point. People cannot "feel" hypertension and hence its existence was known only after an instrument was created capable of measuring blood pressure. Normal and abnormal pressures are defined in terms of units of measure associated with the sphygmomanometer: millimeters of mercury (mm Hg). No pre-existing concept of excessive arterial pressure was tested by constructing a sphygmomanometer. Rather, it appears that application of the device caused physicians to become aware of the health consequences of hyper- and hypo-tension.

Reasons for Conceptual Change

Several reasons can be discerned to explain why so many new instruments result in conceptual change. One reason is that instruments extend our senses in new, and sometimes unanticipated ways. Instruments quantify, often at precisely timed intervals — and thereby reveal temporal patterns at time indices vastly different from ordinary experience and consequently may yield unexpected information. The total unfamiliarity of what is revealed by the new instrument explains why theory is unable to anticipate and guide these developments. For example, high-speed photography can be played back slowly to reveal details of events that would ordinarily happen too quickly to be perceived. Time-lapse photography is used to "speed up" events so that we can perceive changes that would ordinarily happen so slowly as not to create the impression of systematic change. Use of lasers to pulse chemical reactions into partial completion is another example. Obtaining brain scans from conscious subjects provides new information about which areas of the brain mediate psychological functions.

A second reason stems from the organizing function of theory. By structuring our thought and perception, theory also blinds us to alternative possibilities. Had Rhodes been theory guided, he would not have conducted his most revealing experiments. Only by disregarding formalized theory and experimenting with apparatus did Rhodes make his discovery. The extent to which theory limits exploration and restricts creative vision is not often recognized. Put otherwise, we readily accept the value of having certain relationships emphasized but are often unaware that this necessarily means that other possibilities are restricted. The set of predicted outcomes is vastly smaller than the set of possible events; this is a major conceptual contribution of theory. There is little reason to search this vast set of "irrelevant" possibilities. Even if one wanted to investigate them, they could not all be listed. By definition, one cannot exhaustively list the "unknown." Fortunately, instruments are not bound by these theoretical limitations. Sometimes they penetrate unconsidered alternatives and present us with unexpected, anomalous results and thereby focus our attention where no theory previously directed us.

Third, instruments are selective in what they measure because of how they are constructed. Instruments consistently collect data in accordance with design parameters. They observe more objectively and consistently than do people. For example, measured activity is not always concordant with rated activity (cf. Tryon and Pinto, 1994). People are much more easily distracted from a central task. The well-known halo effect is an example.

Methodological

Normal science blends theory and data from new or improved instrumentation. The results from improved instruments are not so large that theory cannot anticipate much of what may be found. Data from improved instruments are often the most certain way of resolving theoretical disputes. A perusal of psychological publications, including dissertation abstracts, clearly indicates that most students and psychologists engage in hypothesis testing rather than instrument development despite the fact that psychological test construction entails considerable theory development and clarification. The absence of adequate measurement does not seem to deter many investigators from hypothesis testing. Rather, psychologists justify hypothesis testing on the basis that they are using the "best available measurement" regardless of how unreliable and invalid the current "state of the art" is. These investigators often recognize that defective instrumentation limits their inferences, but hypothesis testing continues without prior instrument development. At least two explanations exist. First, and most likely, test development is not as scientifically respected as hypothesis testing even though test development entails construct validation which is a highly theoretical enterprise. Perhaps the above documentation regarding the theoretical importance of instrument development will help redress this imbalance. Second, test construction and measurement development are something a few specialized psychologists called psychometricians are perceived as responsible for doing. The rest of us need only use the "best test" at hand. Further measurement compromises are made by using brief test forms, often on the misguided premise that it is better to measure more variables poorly than a few variables well.

A second methodological contribution that psychological testing can make to theory construction stems from the fact that test reliability often substantially exceeds test validity. If a test has a reliability of .9 and a validity of .3, then valid variance (.09) is just one ninth (11.1%) of what the test measures reliably (.81). Theoretical inquiry should be made into what else the test is measuring since this component may be nine times as large as what the test was intended to measure. Instrumentation here points to the possibility of related sources of variance that remain unexplored because theory focuses upon and emphasizes a specific small fraction of the total variance. Psychology might benefit considerably by greater sensitivity to measurement driven theoretical inquiry.

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