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# An Abductive Theory of Scientific Method

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A broad theory of scientific method is sketched that has particular relevance for the behavioral sciences. This theory of method assembles a complex of specific strategies and methods that are used in the detection of empirical phenomena and the subsequent construction of explanatory theories. A characterization of the nature of phenomena is given, and the process of their detection is briefly described in terms of a multistage model of data analysis. The construction of explanatory theories is shown to involve their generation through abductive, or explanatory, reasoning, their development through analogical modeling, and their fuller appraisal in terms of judgments of the best of competing explanations. The nature and limits of this theory of method are discussed in the light of relevant developments in scientific methodology.

*Keywords:* scientific method, phenomena detection, theory construction, abductive reasoning, research methodology



> [T]he attempt to understand and improve methods, and to do so via theorizing them, is at the center of an intelligently evolving cognition (Clifford Hooker, 1987, p. 291)

This article is concerned with scientific method in the behavioral sciences. Its principal goal is to outline a broad theory of scientific method by making use of selected developments in contemporary research methodology. The time now seems right to intensify efforts to assemble knowledge of research methods into larger units of understanding. Currently, behavioral scientists use a plethora of specific research methods and a number of different investigative strategies when studying their domains of interest. Among this diversity, the well-known inductive and hypothetico-deductive accounts of scientific method have brought some order to our investigative practices. The former method speaks to the discovery of empirical generalizations, whereas the latter method is used to test hypotheses and theories in terms of their predictive success.

However, although inductive and hypothetico-deductive methods are commonly regarded as the two main theories of scientific method (Laudan, 1981; and, in fact, are sometimes regarded as the principal claimants for the title of the definitive scientific method), they are better thought of as restrictive accounts of method that can be used to meet specific research goals (Nickles, 1987), not broad accounts of method that pursue a range of research goals. In fashioning empirical generalizations, the inductive method undoubtedly addresses an important part of scientific inquiry. However, it is a part only. Of equal importance is the process of theory construction. Here, however, the hypothetico-deductive method, with its focus on theory testing, speaks only to one, although important, part of the theory construction process (Simon, 1977).

The theory of method outlined in this article is a broader account of scientific method than either the inductive or hypothetico-deductive theories of method. This more comprehensive theory of method endeavors to describe systematically how one can first discover empirical facts and then construct theories to explain those facts. Although scientific inquiry is often portrayed in hypothetico-deductive fashion as an undertaking in which theories are first constructed and facts are then gathered in order to test those theories, this should not be thought of as its natural order. In fact, scientific research frequently proceeds the other way around. The theory of method described here adopts this alternative, facts-before-theory sequence, claiming that it is a search for the understanding of empirical phenomena that gives explanatory theory construction its point. With this theory of method, phenomena exist to be explained rather than serve as the objects of prediction in theory testing.

## Two Theories of Method

Before presenting the proposed theory of scientific method, the well-known inductive and hypothetico-deductive accounts of scientific method are briefly considered.

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This serves to define their proper limits as methods of science and, at the same time, provide useful contrasts to the more comprehensive theory of method.

### Inductive Method

In popular accounts of inductive method (e.g., Chalmers, 1999), the scientist is typically portrayed as reasoning inductively by enumeration from secure observation statements about singular events to laws or theories in accordance with some governing principle of inductive reasoning. Sound inductive reasoning is held to create and justify theories simultaneously, so that there is no need for subsequent empirical testing. Some have criticized this view of method for placing excessive trust in the powers of observation and inductive generalization, and for believing that enumerative induction is all there is to scientific inference. In modern behavioral science, the radical behaviorism of B. F. Skinner is a prominent example of a research tradition that uses an inductive conception of scientific method (Sidman, 1960; Skinner, 1984). Within this behaviorist tradition, the purpose of research is to detect empirical phenomena of learning that are subsequently systematized by nonexplanatory theories.

Although the inductive method has received considerable criticism, especially from those who seek to promote a hypothetico-deductive conception of scientific inquiry, it nevertheless stresses, in a broad-brush way, the scientific importance of fashioning empirical generalizations. Shortly, it is shown that the alternative theory of scientific method to be presented uses the inductive method in the form of enumerative induction, or induction by generalization, in order to detect empirical phenomena.

### Hypothetico-Deductive Method

For more than 150 years, hypothetico-deductivism has been the method of choice in the natural sciences (Laudan, 1981), and it assumed hegemonic status in 20th century psychology (Cattell, 1966). Psychology's textbook presentations of scientific method are often cast in hypothetico-deductive form, and the heavy emphasis psychological researchers have placed on testing hypotheses by using traditional statistical significance test procedures basically conforms to a hypothetic-deductive structure.

The hypothetico-deductive method is standardly portrayed in minimal terms: The researcher is required to take a hypothesis or a theory and test it indirectly by deriving from it one or more observational predictions. These predictions are amenable to direct empirical test. If the predictions are borne out by the data, then that result is taken as a confirming instance of the theory in question. If the predictions fail to square with the data, then that fact counts as a disconfirming instance of the theory. Although tacitly held by many scientists, and endorsed in different ways by prominent philosophers of science (e.g., Hempel, 1966; Popper, 1959), the hypothetico-deductive account of method has been strongly criticized by both philosophers and psychologists (e.g., Cattell, 1966; Glymour, 1980; Rorer, 1991; Rozeboom, 1999).

The central criticism of the hypothetico-deductive method is that it is confirmationally lax. This laxity arises from the fact that any positive confirming instance of a hypothesis obtained by the hypothetico-deductive method can confirm any hypothesis that is conjoined with the test hypothesis, however plausible, or implausible, that conjunct might be. This criticism has prompted some methodologists (e.g., Glymour, 1980; Rozeboom, 1999) to declare that the hypothetico-deductive method is hopeless and should therefore be abandoned. Although this is a fair assessment of the confirmational worth of the orthodox account of the hypothetico-deductive method, it should be noted that the method can be recast in a more sophisticated form and put to useful effect in hypothesis testing research (Giere, 1983). Although the hypothetico-deductive method does not figure as a method of theory appraisal in the comprehensive theory of scientific method presented here, it can play a legitimate role in hypothesis and theory testing. It should thus be seen as complementary to the broader theory of method, not a rival to it. I comment briefly on this matter toward the end of the article.

The theory of method introduced in the next section is a broader theory than both the inductive and hypothetico-deductive theories. However, it should be acknowledged at the outset that it has its own omissions. Most obviously, the method begins by focusing on data analysis and thereby ignores the matters of research design, measurement, and data collection. This is a limit to its comprehensiveness that it shares with the two theories of method just canvassed.

## Overview of the Broad Theory

According to the broad theory of method, scientific inquiry proceeds as follows. Guided by evolving research problems that comprise packages of empirical, conceptual, and methodological constraints, sets of data are analyzed in order to detect robust empirical regularities, or phenomena. Once detected, these phenomena are explained by abductively inferring the existence of underlying causal mechanisms.[1] Here, abductive inference involves reasoning from

[1] The term *causal mechanism* is ambiguous. In the broad theory of method being proposed, the generation of theories involves explanatory inference to claims about the existence of causal entities. It is not until the development of these theories is undertaken that the mechanisms responsible for the production of their effects are identified and spelled out. Also, in this article it is assumed that the productivity of causal mechanisms is distinct from the regularities that they explain (Bogen, 2005; but cf. Woodward, 2003). Of course, this does not preclude the methodological use of generalizations that describe natural regularities in order to help identify the causal mechanisms that produce them.

Table 1
*Submethods and Strategies of the Abductive Theory of Method*

| | Theory construction | | |
|---|---|---|---|
| Phenomena detection | Theory generation | Theory development | Theory appraisal |
| Strategies<br>Control for confounds<br>Calibration of instruments<br>Data analytic strategies<br>Constructive replication | Abductive methods<br>Exploratory factor analysis<br>Grounded theory method<br>Heuristics (e.g., principle of the common cause) | Strategies<br>Analogical modeling | Inference to the best explanation<br>Theory of explanatory coherence |
| Methods<br>Initial data analysis<br>Exploratory data analysis (e.g., stem-and-leaf, box plot)<br>Computer-intensive resampling methods (e.g., bootstrap, jackknife, cross-validation)<br>Meta-analysis | | | |

*Note.* For the most part, particular methods and strategies subsumed by the abductive theory are appropriate either for phenomena detection or for theory construction, but not for both. Exceptions include exploratory factor analysis and grounded theory method, both of which have data analytic components that can contribute to phenomena detection.



phenomena, understood as presumed effects, to their theoretical explanation in terms of underlying causal mechanisms. Upon positive judgments of the initial plausibility of these explanatory theories, attempts are made to elaborate on the nature of the causal mechanisms in question. This is done by constructing plausible models of those mechanisms by analogy with relevant ideas in domains that are well understood. When the theories are well developed, they are assessed against their rivals with respect to their explanatory goodness. This assessment involves making judgments of the best of competing explanations.

An important feature of the broad theory of scientific method is its ability to serve as a framework within which a variety of more specific research methods can be located, conjoined, and used. Operating in this way, these otherwise separate specific research methods can be viewed as submethods of the parent method. In turn, the submethods provide the parent theory with the operational bite that helps it make scientific inquiry possible. Comprehensive methods are often constituted by a number of submethods and strategies that are ordered according to an overarching structure (Ross, 1981). In characterizing the broad theory, I indicate how a number of specific research methods are deployed within its compass. Table 1 contains a variety of research methods and strategies that can be placed within the structure of the comprehensive theory of scientific method. A number of these are discussed in the exposition of the method that follows, but most of them are not required for its characterization.[2] The majority of submethods selected for consideration in the article have been chosen primarily to facilitate the exposition of the processes of phenomena detection and theory construction without attempting to give an essential characterization of these processes.

As a theory of scientific method, the account presented here obviously endeavors to throw some light on the nature of scientific inquiry. It also has some clear implications for the way research is carried out within its purview. However, partly because of its incomplete nature, the theory is not accompanied by a set of instructions for its ready implementation. Such an accompaniment awaits a fuller account of the method and would have to be modified as a function of the nature of the submethods chosen to operate within it.

Because of the prominence of abductive reasoning in this broad theory of method, I henceforth refer to it as the *abductive theory of method* (ATOM). The exposition of the method begins with an account of phenomena detection and then considers the process of constructing explanatory theories. Toward the end of the article, two pairs of important methodological ideas that feature prominently in ATOM are examined. The article concludes with a discussion of the nature and limits of the method.

## Phenomena Detection

Scientists and philosophers often speak as though science is principally concerned with establishing direct relationships between observation and theory. There is empirical evidence that psychologists speak, and sometimes think, in this way (Clark & Paivio, 1989), whereas philosophers of science of different persuasions often say that scientific theories are evaluated with respect to statements about

[2] Note, however, that the strategy of analogical modeling is essential for theory development in the abductive theory of method and that the theory of explanatory coherence does heavy-duty work in the abductive theory of method because it is the best developed method of inference to the best explanation currently available.

relevant data (Bogen & Woodward, 1988). Despite what they say, scientists frequently behave in accord with the view that theories relate directly to claims about phenomena, such as empirical generalizations, not data, while in turn, claims about phenomena relate directly to claims about data. That is, talk of a direct relationship between data and theory is at variance with empirical research practice, which often works with a threefold distinction between data, phenomena, and theory.

As just noted, ATOM assigns major importance to the task of detecting empirical phenomena, and it views the completion of this task as a requirement for subsequent theory construction. This section of the article discusses the process of phenomena detection in psychological research. First, the distinction between data and phenomena is drawn. Then, a multistage model of data analysis is outlined. This model serves to indicate one way in which a variety of statistical methods available to psychologists can be combined in phenomena detection.



### *The Nature of Phenomena*

Bogen and Woodward (1988; Woodward, 1989, 2000) have argued in detail that it is claims about phenomena, not data, that theories typically seek to predict and explain and that, in turn, it is the proper role of data to provide the observational evidence for phenomena, not for theories. Phenomena are relatively stable, recurrent, general features of the world that, as researchers, we seek to explain. The more striking of them are often called *effects*, and they are sometimes named after their principal discoverer. The so-called phenomenal laws of physics are paradigmatic cases of claims about phenomena. By contrast, the so-called fundamental laws of physics explain the phenomenal laws about the relevant phenomena. For example, the electron theory of Lorentz is a fundamental law that explains Airy's phenomenological law of Faraday's electro-optical effect (Cartwright, 1983). Examples of the innumerable phenomena claims in psychology include the matching law (the law of effect), the Flynn effect of intergenerational gains in IQ, and recency effects in human memory.

Although phenomena commonly take the form of empirical regularities, they comprise a varied ontological bag that includes objects, states, processes, events, and other features that are hard to classify. Because of this variety, it is generally more appropriate to characterize phenomena in terms of their role in relation to explanation and prediction (Bogen & Woodward, 1988). For example, the relevant empirical generalizations in cognitive psychology might be the objects of explanations in evolutionary psychology that appeal to mechanisms of adaptation, and those mechanisms might in turn serve as phenomena to be explained by appealing to the mechanisms of natural selection in evolutionary biology.

Phenomena are frequently taken as the proper objects of scientific explanation because they are stable and general. Among other things, systematic explanations require one to show that the events to be explained result from the causal factors appealed to in the explanation. They also serve to unify the events to be explained. Because of their ephemeral nature, data will not admit of systematic explanations.

In order to understand the process of phenomena detection, phenomena must be distinguished from data. Unlike phenomena, data are idiosyncratic to particular investigative contexts. Because data result from the interaction of a large number of causal factors, they are not as stable and general as phenomena, which are produced by a relatively small number of causal factors. Data are ephemeral and pliable, whereas phenomena are robust and stubborn. Phenomena have a stability and repeatability that is demonstrated through the use of different procedures that often engage different kinds of data. Data are recordings or reports that are perceptually accessible; they are observable and open to public inspection. Despite the popular view to the contrary, phenomena are not, in general, observable; they are abstractions wrought from the relevant data, frequently as a result of a reductive process of data analysis. As Cartwright (1983) remarked in her discussion of phenomenal and theoretical laws in physics, “the distinction between theoretical and phenomenological has nothing to do with what is observable and what is unobservable. Instead the terms separate laws which are fundamental and explanatory from those that merely describe” (p. 2). Examples of data, which serve as evidence for the aforementioned psychological effects, are rates of operant responding (evidence for the matching law), consistent intergenerational IQ score gains (evidence for the Flynn effect), and error rates in psychological experiments (evidence for recency effects in short-term memory).

The methodological importance of data lies in the fact that they serve as evidence for the phenomena under investigation. In detecting phenomena, one extracts a signal (the phenomenon) from a sea of noise (the data). Some phenomena are rare, and many are difficult to detect; as Woodward (1989) noted, detecting phenomena can be like looking for a needle in a haystack. It is for this reason that, when extracting phenomena from the data, one often engages in data exploration and reduction by using graphical and statistical methods.

### *A Model of Data Analysis*

In order to establish that data are reliable evidence for the existence of phenomena, scientists use a variety of methodological strategies. These strategies include controlling for confounding factors (both experimentally and statistically), empirically investigating equipment (including the calibration of instruments), engaging in data analytic strategies of both statistical and nonstatistical kinds, and constructively replicating study results. As can be seen in Table 1, these procedures are used in the detection of phenomena, but they are not used in the construction of explanatory theory (cf. Franklin, 1990; Woodward, 1989). The later discussion of the importance of reliability in the process of phenomena detection helps indicate why this is so.

Given the importance of the detailed examination of data in the process of phenomena detection, it is natural that the statistical analysis of data figures prominently in that exercise. A statistically oriented, multistage account of data analysis is therefore outlined in order to further characterize the phenomena detection phase of ATOM. The model proceeds through the four stages of initial data analysis, exploratory data analysis, close replication, and constructive replication. However, it should be noted that, although the behavioral sciences make heavy use of statistical methods in data analysis, qualitative data analytic methods can also be used in the detection of phenomena (cf. Strauss, 1987).

*Initial data analysis.* The initial examination of data (Chatfield, 1985) refers to the first informal scrutiny and description of data that is undertaken before exploratory data analysis proper begins. It involves screening the data for its quality. Initial data analysis variously involves checking for the accuracy of data entries, identifying and dealing with missing and outlying data, and examining the data for their fit to the assumptions of the data analytic methods to be used. Data screening thus enables one to assess the suitability of the data for the type of analysis intended.

This important, and time-consuming, preparatory phase of data analysis has failed to receive the amount of explicit attention that it deserves in behavioral science education. Recently, however, the American Psychological Association's Task Force on Statistical Inference (Wilkinson & the Task Force on Statistical Inference, 1999) recommended changes to current practices in data analysis that are broadly in keeping with the goals of initial data analysis. Fidell and Tabachnick (2003) provided a useful overview of the importance of the work required to identify and correct problems in data.

It should be clear, even from these brief remarks, that the initial examination of data is a requirement of successful data analysis in science, for data that lack integrity can easily result in the misuse of data analytic methods and the drawing of erroneous conclusions.

*Exploratory data analysis.* Exploratory data analysis uses multiple forms of description and display and involves descriptive, and frequently quantitative, detective work designed to reveal the structure or patterns in the data under scrutiny (Behrens & Yu, 2003; Tukey, 1977).[3] The exploratory data analyst is encouraged to undertake an unfettered investigation of the data and perform multiple analyses using a variety of intuitively appealing and easily used techniques.

The compendium of methods for the exploration of data is designed to facilitate both the discovery and the communication of information about data. These methods are concerned with the effective organization of data, the construction of graphical displays, and the examination of distributional assumptions and functional dependencies. The stem-and-leaf display and the box-and-whisker plot are two well-known exploratory methods.

Two attractive features of exploratory methods are their robustness to changes in underlying distributions and their resistance to outliers in data sets. Exploratory methods with these two features are particularly suited to data analysis in the behavioral sciences, where researchers are frequently confronted with ad hoc data sets on manifest variables that have been acquired in convenient ways.

*Close replication.* Successfully conducted exploratory analyses will suggest potentially interesting data patterns. However, it will normally be necessary to check on the stability of the emergent data patterns through use of confirmatory data analysis procedures. Computer-intensive resampling methods such as the bootstrap, the jackknife, and cross-validation (Efron & Tibshirani, 1993) constitute an important set of confirmatory procedures that are well suited to the demands of modern data analysis. Such methods free us, as researchers, from the assumptions of orthodox statistical theory, and permit us to gauge the reliability of chosen statistics by making thousands, even millions, of calculations on many data points. Statistical resampling methods like these are used to establish the consistency, or reliability, of sample results. In doing this, they provide us with the kind of validating strategy that is needed to achieve close replications.[4]

Now that psychology has finally begun to embrace exploratory data analysis, one can hope for a corresponding increase in the companionate use of statistical resampling methods in order to ascertain the validity of the data patterns initially suggested by the use of exploratory methods.

*Constructive replication.* In establishing the existence of phenomena, it is necessary that science undertake both close and constructive replications. The statistical resampling methods just mentioned are concerned with the con-

[3] Behrens and Yu suggested that the inferential foundations of exploratory data analysis are to be found in the notion of abduction. By contrast, ATOM regards exploratory data analysis as a descriptive pattern detection process that is a precursor to the inductive generalizations involved in phenomena detection. Abductive inference is reserved for the construction of causal explanatory theories that are introduced to explain empirical phenomena. Behrens and Yu's suggestion conflates description and explanation in this regard.

[4] Statistical resampling methods can be used in a hypothetico-deductive manner within ATOM in order to test descriptive hypotheses that are suggested by exploratory data analytic work. However, this use of the hypothetico-deductive method should be distinguished from its use to evaluate explanatory hypotheses and theories. The latter takes place outside the methodological space provided by ATOM.

sistency of sample results that help researchers achieve close, or internal, replications. By contrast, constructive replications are undertaken to demonstrate the extent to which results hold across different methods, treatments, and occasions. In other words, constructive replication is a triangulation strategy designed to ascertain the generalizability of the results identified by successful close replication (Lindsay & Ehrenberg, 1993). Constructive replication, in which researchers vary the salient conditions, is a time-honored strategy for justifying claims about phenomena.

In recognition of the need to use statistical methods that are in keeping with the practice of describing predictable phenomena, researchers should seek the generalizability of relationships rather than their statistical significance (Ehrenberg & Bound, 1993)—hence, the need to use observational and experimental studies with multiple sets of data, observed under quite different sets of conditions. The recommended task here is not to figure what model best fits a single set of data but to ascertain whether the model holds across different data sets. Seeking reproducible results through constructive replications, then, requires data analytic strategies that are designed to detect significant sameness rather than significant difference.

The four-stage model of data analysis just outlined assists in the detection of phenomena by attending in turn to data quality, pattern suggestion, pattern confirmation, and generalization. In effect, this process is one of enumerative induction in which one learns empirically, on a case-by-case basis, the conditions of applicability of the empirical generalizations that represent the phenomena. Thus, as noted earlier, the importance of inductive reasoning shown by the traditional inductive method is shared by ATOM's account of phenomena detection.

It bears repeating that this model of data analysis is clearly not the only way in which phenomena detection can be achieved. In addition to the several strategies of phenomena detection mentioned earlier, meta-analysis is a prominent example of a distinctive use of statistical methods by behavioral scientists to aid in the detection of phenomena. As is well-known, meta-analysis is widely used to conduct quantitative literature reviews. It is an approach to data analysis that involves the quantitative analysis of the data analyses of primary empirical studies. By calculating effect sizes across primary studies in a common domain, meta-analysis helps researchers detect general positive effects (cf. Schmidt, 1992). By using statistical methods to ascertain the existence of robust empirical regularities, meta-analysis can be usefully viewed as the statistical analogue of direct experimental replication. It is in this role that meta-analysis currently performs its most important work in science. Contrary to the claims made by some of its critics in psychology (e.g., Sohn, 1996), meta-analysis can be regarded as a legitimate and important means of detecting empirical phenomena in the behavioral sciences (Gage, 1996).

## Theory Construction

Detecting empirical phenomena is a major goal of scientific research, and their successful detection constitutes an important type of scientific discovery in its own right. However, once detected, phenomena serve the important function of prompting the search for their own understanding. This understanding is commonly met in science by constructing relevant explanatory theories.

For inductivists, inductively grounded conclusions about phenomena are of paramount importance. However, although inductivists often subsequently construct theories, their theories do not provide explanations of phenomena that appeal to causal mechanisms. Instead, their theories function as tools or instruments concerned with the description, economical ordering, and prediction of empirical relationships. For hypothetico-deductivists, theories are said to be generated amethodologically through free use of the imagination (Hempel, 1966; Popper, 1959). Theories obtained in this manner are often regarded as explanatory in nature, but their worth is principally judged in terms of their predictive success, rather than their ability to explain empirical phenomena.

ATOM, by contrast, maintains that theory construction is neither inductive nor amethodological. For it, theory construction comprises three methodological phases: theory generation, theory development, and theory appraisal. These phases do not occur in a strictly temporal order, for although theory generation precedes theory development, theory appraisal begins with theory generation, continues with theory development, and extends to the comparative appraisal of well-developed theories. Further, ATOM's characterization of theory construction is abductive through and through: Theory generation, theory development, and theory appraisal are all portrayed as abductive, or explanatory, undertakings, although the form of abduction is different in each case. The account of theory construction that follows articulates the abductive character of each of the three phases.

### Theory Generation

*Abductive inference.* This section begins with a general characterization of the type of abductive reasoning that is often involved in theory generation. It is followed by a discussion of the method of exploratory factor analysis that is presented as a prominent example in psychology of an abductive method of theory generation. The discussion of exploratory factor analysis, therefore, serves as an optional and restricted account of theory generation for ATOM. The characterizations of abduction and factor analysis are adapted from Haig (2005).

The basic idea of abductive inference can be usefully traced back to the American philosopher and scientist Charles Sanders Peirce (1931–1958). More recent developments in the fields of philosophy of science and artificial intelligence (e.g., Josephson & Josephson, 1994; Magnani, 2001; Thagard, 1988, 1992) have built on Peirce's ideas to significantly advance researchers' understanding of abductive reasoning.

Abduction is a form of reasoning involved in both the generation and evaluation of explanatory hypotheses and theories. For Peirce (1931–1958), "abduction consists in studying the facts and devising a theory to explain them" (Vol. 5, 1934, p. 90). It is "[t]he first starting of an hypothesis and the entertaining of it, whether as a simple interrogation or with any degree of confidence" (Vol. 6, 1934, p. 358).

Traditionally, abduction was thought to take its place at the inception of scientific hypotheses, where it often involves making an inference from puzzling facts to hypotheses that might well explain them. However, there are a number of different ways in which explanatory hypotheses can be abductively obtained. In focusing on the generation of hypotheses, Thagard (1988) helpfully distinguished between existential and analogical abduction. As he put it, "Existential abduction postulates the existence of previously unknown objects, such as new planets, . . . [whereas] analogical abduction uses past cases of hypothesis formation to generate hypotheses similar to existing ones" (p. 54). Existential abduction is the type of abduction centrally involved in the factor analytic generation of explanatory hypotheses. Later, it is shown that the theory development phase of ATOM adopts a modeling strategy that involves analogical abduction, and its approach to comparative theory appraisal uses a further form of abduction known as *inference to the best explanation.*

Existential abduction can be characterized in the following general schema:

> The surprising empirical phenomenon, P, is detected.
> But if hypothesis H were approximately true, and the relevant auxiliary knowledge, A, was invoked, then P would follow as a matter of course.
> Hence, there are grounds for judging H to be initially plausible and worthy of further pursuit.

This schematic characterization of existential abduction, as it occurs within the theory generation phase of ATOM, is coarse grained and far from sufficient. It should, therefore, be understood in the light of the following supplementary remarks.

First, as indicated in the discussion of phenomena detection, the facts to be explained in science are not normally particular events, but empirical generalizations or phenomena, and, strictly speaking, they are not typically observed.

Second, confirmation theory in the philosophy of science, and the nature of the hypothetico-deductive method in particular, make it clear that the facts, or phenomena, are derived not just from the proposed theory but from that theory in conjunction with accepted auxiliary claims taken from relevant background knowledge.

Third, the antecedent of the conditional assertion in the second premise of the argument schema should not be taken to imply that abductive inferences produce truths as a matter of course. Although science aims to provide true, or approximately true, theories of the world, the supposition that the proposed theory be true is not a requirement for the derivation of the relevant facts. All that is required is that the theory be plausible enough to be provisionally accepted. It is important to distinguish between *truth,* understood as a guiding ideal for science (a goal that we, as scientists, strive for but never fully reach), and the *justification* of theories, which is based on epistemic criteria such as predictive success, simplicity, and explanatory breadth. As proxies for truth, justificatory criteria such as these are indicative of truth, but they are not constitutive of truth.

Fourth, it should be noted that the conclusion of the argument schema does not assert that the hypothesis itself is true, only that there are grounds for thinking that the proposed hypothesis might be true. This is a weaker claim that allows one to think of a sound abductive argument as delivering a judgment that the hypothesis is initially plausible and worthy of further pursuit. Assessments of initial plausibility constitute a form of justification that involves reasoning from warranted premises to an acceptance of the knowledge claims in question. This form of justification is discussed later in the section on ATOM and Scientific Methodology.

Fifth, the schema depicting abductive inference focuses on its logical form only. It is, therefore, of limited value in understanding the theory construction process unless it is combined with a set of regulative constraints that enable us to view existential abduction as an inference, not just to any conceivable explanation, but to a plausible explanation. The description of research problems presented later indicates that the constraints that regulate the abductive generation of scientific theories comprise a host of heuristics, rules, and principles that govern what counts as good explanations.

*Exploratory factor analysis.* Unfortunately, there is a dearth of codified abductive methods available for ready use in the behavioral sciences. A notable exception is the method of exploratory factor analysis. Exploratory factor analysis is designed to facilitate the postulation of latent variables that are thought to underlie patterns of correlations in new domains of manifest variables. It does this by using multiple regression and partial correlation theory to model sets of manifest or observed variables in terms of linear functions of other sets of latent, or unobserved, variables. Although the nature and purpose of exploratory factor analysis is a matter of some debate, it can plausibly be understood as an abductive method of theory generation (Haig, 2005; Rozeboom, 1972; Stephenson, 1961).[5] This characterization of the inferential nature of exploratory factor analysis is seldom given in expositions of the method; however, it is an interpretation that coheres well with its general acceptance as a latent variable method.

On this interpretation, exploratory factor analysis facilitates the achievement of useful existential abductions, although for this to happen, the method must be used in an exemplary manner (cf. Fabrigar, Wegener, MacCallum, & Strahan, 1999; Preacher & MacCallum, 2003) with circumspect interpretation of the factors. As noted earlier, existential abductions enable us, as researchers, to hypothesize the existence of entities previously unknown to us. The innumerable examples of existential abduction in science include the initial postulation of hidden entities such as atoms, genes, tectonic plates, and personality traits. In cases like these, the primary thrust of the initial abductive inferences is to claims about the existence of theoretical entities[6] in order to explain empirical facts or phenomena. Similarly, the hypotheses given to us through the use of exploratory factor analysis postulate the existence of latent variables such as Spearman's *g* and extraversion. It remains for further research to elaborate on the first rudimentary conception of these variables.

The factor analytic use of existential abduction to infer the existence of, say, the theoretical entity *g* can be coarsely reconstructed in accordance with the aforementioned schema for abductive inference along the following lines:

> The surprising empirical phenomenon known as the *positive manifold*[7] is identified.
> If *g* exists, and it is validly and reliably measured by a Wechsler intelligence scale (and/or some other objective test), then the positive manifold would follow as a matter of course.
> Hence, there are grounds for judging the hypothesis of *g* to be initially plausible and worthy of further pursuit.

This example serves to illustrate the point that the method of exploratory factor analysis proper should be taken to include the factor analyst's substantive interpretation of the statistical factors. It is important to realize that the factor analyst has to resort to his or her own abductive powers when reasoning from correlational data patterns to underlying common causes. Note that the schema for abductive inference, and its application to the generation of Spearman's hypothesis of *g*, are concerned with the form of the arguments involved, not with the actual generation of the explanatory hypotheses. In each case, the explanatory hypothesis is given in the second premise of the argument. An account of the genesis of the explanatory hypothesis must, therefore, be furnished by some other means. It is plausible to suggest that reasoning to explanatory hypotheses trades on human beings' evolved cognitive ability to abductively generate such hypotheses. Peirce (1931–1958) himself maintained that the human ability to engage readily in abductive reasoning was founded on a guessing instinct that has its origins in evolution. More suggestively, Carruthers (2002) maintained that our ability, as humans, to engage in explanatory inference is almost certainly largely innate, and he speculated that it may be an adaptation selected for because of its crucial role in the fitness-enhancing activities of our ancestors such as hunting and tracking. Whatever its origin, an informative methodological characterization of the abductive nature of factor analytic inference must appeal to the scientist's own psychological resources as well as those of logic.

Exploratory factor analysis, then, can usefully function as a submethod of ATOM by being located in that theory's context of theory generation. Although it exemplifies well the character of existential abduction, exploratory factor analysis is clearly not an all-purpose method for abductively generating explanatory hypotheses and theories. With its focus on common factors, it can properly serve as a generator of elementary theories only in those multivariate domains where there are common causal structures.

Understood in the context of theory generation, methods of existential abduction like exploratory factor analysis should not be expected to achieve highly developed and well-validated scientific theories. At best, they deliver rudimentary theories that have initial plausibility. It is important to realize that these abductive methods enable us to justify the initial plausibility of the theories they spawn. The very process of the abductive generation of theories has a bearing on the first determinations of their worth, in that we appeal to the soundness of the abductive arguments used in the introduction of theories in order to evaluate their early epistemic promise (cf. Whitt, 1992).

Relatedly, the nascent theories bequeathed us by methods like exploratory factor analysis postulate the existence of hidden causal mechanisms, but they do not provide an informative characterization of their nature. Such theories have the status of dispositional theories in that they provide us with oblique characterizations of the properties we attribute to things by way of their presumed effects under

[5] Some take exploratory factor analysis to be a data analytic method, only. My principal reason for assigning a theory generation role to exploratory factor analysis is based on the belief that factors are best regarded as latent common causes and that inference to such causes is abductive in nature (Haig, 2005).

[6] The term *entity* is used as a catch-all ontological term that covers a miscellany of properties that includes states, processes, and events. Although existential abductions in exploratory factor analysis are to properties expressed as the values of variables, not all existential abductions need take this form.

[7] The *positive manifold* is a term that is sometimes used to refer to the striking, and well-established, fact that almost all different tests of ability correlate positively with one another to a significant degree. Despite its historical link to Spearman's theory of general intelligence, the positive manifold can be taken as evidence for the existence of two or more factors.

specified conditions (cf. Mumford, 1998). A move beyond the rudimentary nature of their dispositional characterization requires subsequent elaboration. It is to a strategy for developing such theories that I now turn.

### Theory Development

*Models in science.* The standard inductive and hypothetico-deductive views of scientific method give little attention to the process of theory development. The use of traditional inductive method leads to theories that are organized summaries of their constituent empirical generalizations, and the orthodox hypothetico-deductive method assumes that hypotheses and theories emerge fully formed, ready for immediate testing.

In contrast to these two theories of scientific method, ATOM is concerned with the development of explanatory theories. As just noted, the theories it generates through existential abduction are dispositional in nature, and explicit provision has to be made for their development before they are systematically evaluated against rival theories with respect to their explanatory goodness. As noted earlier, ATOM recommends that this be done by building analogical models of the causal mechanisms in question.

There is a long-held view (e.g., Duhem, 1914/1954), still popular in some quarters, that analogical models are dispensable aids to formulating and understanding scientific theories. This negative view of the cognitive value of analogical models in science contrasts with the positive view that they are an essential part of the development of theories (cf. Campbell, 1920; Harré, 1976; Hesse, 1966). Contemporary studies of scientific practice, including philosophy of science, frequently accord analogical models a genuine, indispensable, cognitive role in science (e.g., Abrantes, 1999; Giere, 1988; Harré, 1988).

Science uses different types of models for different purposes. For example, iconic models[8] are constructed to provide a good resemblance to the object or property being modeled, mathematical models offer an abstract symbolic representation of the domain of interest, and analogue models express relevant relations of analogy between the model and the reality being represented. Harré (1970) contains a useful taxonomy of this variety. Although it is acknowledged that there is a need to use a variety of different modeling strategies in science, ATOM adopts the strategy of using analogical models to help develop explanatory theories. Because analogical modeling is a strategy that increases the content of explanatory theories, its reasoning takes the form of analogical abduction.

*Analogical modeling.* The idea that analogical models are important in the development of scientific theories can be traced back to Campbell (1920). Although analogies are not always used in scientific explanation, their role in theory development within ATOM is of central importance. The need for analogical modeling within ATOM stems from two features of its characterization of theory generation. First, as with exploratory factor analysis, the abductive generation of theories takes the form of existential abduction, through which the existence of theoretical entities is postulated. Therefore, an appropriate research strategy is required to learn about the nature of these hidden entities. For this, the strategy of analogical modeling is used to do the required elaborative work. Second, recall that the postulation of theoretical entities through existential abduction confers an assessment of initial plausibility on those postulations. However, for claims about those latent entities to have the status of genuine knowledge, further evaluative work has to be done. The construction of appropriate analogical models serves to assess the plausibility of our expanded understanding, as well as to expand our understanding of those entities.

For ATOM, theory development expands our knowledge of the nature of our theories' causal mechanisms. This is achieved by using the pragmatic strategy of conceiving of these unknown mechanisms in terms of what is already familiar and well understood. Well known examples of models that have resulted from this strategy are the molecular model of gases, based on an analogy with billiard balls in a container; the model of natural selection, based on an analogy with artificial selection; and the computational model of the mind, based on an analogy with the computer.

To understand the nature of analogical modeling, it is helpful to distinguish between a model, the source of the model, and the subject of the model (Harré, 1976; Hesse, 1966). From the known nature and behavior of the source, one builds an analogical model of the unknown subject or causal mechanism. If we take the biological example just mentioned, Darwin fashioned his model of the subject of natural selection by reasoning by analogy from the source of the known nature and behavior of the process of artificial selection. In this way, analogical models play an important creative role in theory development. However, this role requires the source, from which the model is drawn, to be different from the subject that is modeled. For example, the modern computer is a well-known source for the modeling of human cognition, though our cognitive apparatus is not generally thought to be a real computer. Models in which the source and the subject are different are sometimes called *paramorphs*. Models in which the source and the subject are the same are sometimes called *homoeomorphs* (Harré,

[8] More precisely, iconic models are constructed as representations of reality, real or imagined. In ATOM they stand in for the hypothesized causal mechanisms. Although representations, iconic models are themselves things, structures, or processes that correspond in some way with things, structures, or processes that are the objects of modeling. They are, therefore, the sorts of things sentences can be about (Harré, 1976).

1976). The paramorph can be an iconic, or pictorial, representation of real or imagined things. It is iconic paramorphs that feature centrally in the creative process of theory development through analogical modeling.

In evaluating the aptness of an analogical model, the analogy between its source and subject must be assessed, and for this one needs to consider the structure of analogies. The structure of analogies in models comprises a positive analogy in which the source and subject are alike, a negative analogy in which the source and subject are unlike, and a neutral analogy where we have no reliable knowledge about matched attributes in the source and subject of the model. The negative analogy is irrelevant for purposes of analogical modeling. Because we are essentially ignorant of the nature of the hypothetical mechanism of the subject apart from our knowledge of the source of the model, we are unable to specify any negative analogy between the model and the mechanism being modeled. Thus, in considering the plausibility of an analogical model, one considers the balance of the positive and neutral analogies (Harré, 1976). This is where the relevance of the source for the model is spelled out. As is shown in the next section, ATOM subscribes to a view of comparative theory appraisal that takes good analogies as a criterion of explanatory worth.

Analogical reasoning is important in science and clearly lies at the inferential heart of analogical modeling. However, as noted above, because the theories fashioned by ATOM are explanatory theories, the analogical models involved in theory development will involve explanatory analogical reasoning, that is, analogical abduction. The reasoning involved in analogical abduction can be simply stated in the form of a general argument schema as follows:

Hypothesis H* about property Q was correct in situation S1.
Situation S1 is like the situation S2 in relevant respects.
Therefore, an analogue of H* might be appropriate in situation S2.

Darwin's theory or model of natural selection, and the other aforementioned analogical models, can plausibly be construed to be based on analogical abduction. The general argument for analogical abduction just given can be rewritten in simplified form for Darwin's case as schema follows:

The hypothesis of evolution by artificial selection was correct in cases of selective domestic breeding.
Cases of selective domestic breeding are like cases of the natural evolution of species with respect to the selection process.
Therefore, by analogy with the hypothesis of artificial selection, the hypothesis of natural selection might be appropriate in situations where variants are not deliberately selected for.

The methodology of modeling through analogical abduction is quite well developed and provides a general, though useful, source of guidance for behavioral scientists. Instructively for psychology, Harré (Harré & Secord, 1972) followed his own account of analogical modeling to construct a rule model of microsocial interaction in social psychology. Here, Goffman's (1969) dramaturgical perspective provides the source model for understanding the underlying causal mechanisms involved in the production of ceremonial, argumentative, and other forms of social interaction.

Thus far, it has been suggested that, for ATOM, the epistemic worth of hypotheses and theories generated by existential abduction are evaluated in terms of their initial plausibility and that these assessments are subsequently augmented by judgments of the appropriateness of the analogies that function as source models for their development. However, with ATOM, well-developed theories are appraised further with respect to a number of additional criteria that are used when judgments about the best of competing explanatory theories are made.

### *Theory Appraisal*

Contemporary scientific methodology boasts a number of general approaches to the evaluation of scientific theories. Prominent among these are the hypothetico-deductive method, which evaluates theories in terms of predictive success; Bayesian accounts of confirmation, which assign probabilities to hypotheses via Bayes's theorem; and inference to the best explanation, which accepts a theory when it is judged to provide a better explanation of the evidence than its rivals do. Of these three approaches, the hypothetico-deductive method is by far the most widely used in psychology (cf. Cattell, 1966; Rorer, 1991; Rozeboom, 1999). Despite occasional urgings (e.g., Edwards, Lindman, & Savage, 1963; Lee & Wagenmakers, 2005; Rorer, 1991), psychologists have been reluctant to use Bayesian statistical methods to test their research hypotheses, preferring instead to perpetuate the orthodoxy of classical statistical significance testing within a hypothetico-deductive framework. Despite the fact that inference to the best explanation is frequently used in science, and extensively discussed in the philosophy of science, it is virtually unheard of, let alone used, to appraise theories in psychology.

True to its name, ATOM adopts an abductive perspective on theory evaluation by using a method of inference to the best explanation. It is shown shortly that, in contrast to the hypothetico-deductive method, ATOM adopts an approach to inference to the best explanation that measures empirical adequacy in terms of explanatory breadth, not predictive success, and, in contrast with Bayesianism, it takes theory evaluation to be an exercise that focuses directly on explanation, not a statistical undertaking in which one assigns probabilities to theories. The basic justification for using inference to the best explanation when evaluating explanatory theories is that it is the only method researchers have that explicitly assesses such theories in terms of the scientific goal of explanatory worth.

In considering theory evaluation in ATOM, the idea of inference to the best explanation is introduced. Then, a well-developed method of inference to the best explanation is presented and discussed. Thereafter, inference to the best explanation is defended as an important perspective on theory evaluation.

*Inference to the best explanation.* In accordance with its name, inference to the best explanation is founded on the belief that much of what we know about the world is based on considerations of explanatory worth. Being concerned with explanatory reasoning, inference to the best explanation is a form of abduction. As mentioned earlier, it involves accepting a theory when it is judged to provide a better explanation of the evidence than its rivals do. In science, inference to the best explanation is often used to adjudicate between well-developed, competing theories (cf. Thagard, 1988).

A number of writers have elucidated the notion of inference to the best explanation (e.g., Day & Kincaid, 1994; Lipton, 2004; Thagard, 1988). The most prominent account is due to Lipton, who suggested that inference to the best explanation is not an inference to the "likeliest" explanation, but to the "loveliest" explanation, where the loveliest explanation comprises the various explanatory virtues such as theoretical elegance, simplicity, and coherence; it is the explanatory virtues that provide the guide to inference about causes in science. However, the most developed formulation of inference to the best explanation as a method of theory evaluation was provided by Thagard (1992). Thagard's formulation of inference to the best explanation identifies, and systematically uses, a number of evaluative criteria in a way that has been shown to produce reliable judgments of best explanation in science. For this reason it is adopted as the method of choice for theory evaluation in ATOM.

*The theory of explanatory coherence.* Thagard's (1992) account of inference to the best explanation is known as the *theory of explanatory coherence* (TEC). According to TEC, inference to the best explanation is centrally concerned with establishing relations of explanatory coherence. To infer that a theory is the best explanation is to judge it as more explanatorily coherent than its rivals. TEC is not a general theory of coherence that subsumes different forms of coherence such as logical and probabilistic coherence. Rather, it is a theory of explanatory coherence in which the propositions hold together because of their explanatory relations.

Relations of explanatory coherence are established through the operation of seven principles. These principles are symmetry, explanation, analogy, data priority, contradiction, competition, and acceptability. The determination of the explanatory coherence of a theory is made in terms of three criteria: consilience, simplicity, and analogy (Thagard, 1988). I next consider the criteria, and then the principles.

The criterion of *consilience*, or explanatory breadth, is the most important criterion for choosing the best explanation. It captures the idea that a theory is more explanatorily coherent than its rivals if it explains a greater range of facts. For example, Darwin's theory of evolution explained a wide variety of facts that could not be explained by the accepted creationist explanation of the time. Consilience can be static or dynamic. *Static consilience* judges all the different types of facts available. *Dynamic consilience* obtains when a theory comes to explain more classes of fact than it did at the time of its inception. A successful new prediction that is also an explanation can often be taken as a sign of dynamic consilience.

The notion of simplicity that Thagard (1988) deemed the most appropriate for theory choice is a pragmatic notion that is closely related to explanation; it is captured by the idea that preference should be given to theories that make fewer special or ad hoc assumptions. Thagard regarded simplicity as the most important constraint on consilience; one should not sacrifice simplicity through ad hoc adjustments to a theory in order to enhance its consilience. Darwin believed that the auxiliary hypotheses he invoked to explain facts, such as the gaps in the fossil record, offered a simpler explanation than the alternative creationist account.

Finally, analogy is an important criterion of inference to the best explanation because it can improve the explanation offered by a theory. Thus, as noted in the earlier discussion of analogical modeling, the explanatory value of Darwin's theory of natural selection was enhanced by its analogical connection to the already understood process of artificial selection. Explanations are judged more coherent if they are supported by analogy to theories that scientists already find credible.

Within TEC, each of the three criteria of explanatory breadth, simplicity, and analogy are embedded in one or more of the seven principles. Thagard (1992, 2000) formulated these principles in both formal and informal terms. They are stated here informally in his words as follows (Thagard, 2000):

1. *Symmetry.* Explanatory coherence is a symmetric relation, unlike, say, conditional probability. That is, two propositions *p* and *q* cohere with each other equally.

2. *Explanation.* (a) A hypothesis coheres with what it explains, which can either be evidence or another hypothesis. (b) Hypotheses that together explain some other proposition cohere with each other. (c) The more hypotheses it takes to explain something, the lower the degree of coherence.

3. *Analogy.* Similar hypotheses that explain similar pieces of evidence cohere.

4. *Data Priority.* Propositions that describe the results of observations have a degree of acceptability on their own.

5. *Contradiction.* Contradictory propositions are incoherent with each other.

6. *Competition.* If *p* and *q* both explain a proposition, and if *p* and *q* are not explanatorily connected, then *p* and *q* are incoherent with each other (*p* and *q* are explanatorily connected if one explains the other or if together they explain something).

7. *Acceptance.* The acceptability of a proposition in a system of propositions depends on its coherence with them. (p. 43)

Limitations of space preclude a discussion of these principles; however, the following points should be noted. The principle of explanation is the most important principle in determining explanatory coherence because it establishes most of the coherence relations. The principle of analogy is the same as the criterion of analogy, where the analogy must be explanatory in nature. With the principle of data priority, the reliability of claims about observations and generalizations, or empirical phenomena, will often be sufficient grounds for their acceptance. The principle of competition allows noncontradictory theories to compete with each other.[9] Finally, with the principle of acceptance, the overall coherence of a theory is obtained by considering the pairwise coherence relations through use of Principles 1–6.

The principles of TEC combine in a computer program, ECHO (Explanatory Coherence by Harmany[10] Optimization), to provide judgments of the explanatory coherence of competing theories. This computer program is connectionist in nature and uses parallel constraint satisfaction to accept and reject theories based on their explanatory coherence.

The theory of explanatory coherence has a number of virtues that make it an attractive theory of inference to the best explanation: It satisfies the demand for justification by appeal to explanatory considerations rather than predictive success; it takes theory evaluation to be a comparative matter; it can be readily implemented by, and indeed is instantiated in, the computer program, ECHO, while still leaving an important place for judgment by the researcher; and it effectively accounts for a number of important episodes of theory assessment in the history of science. In short, TEC and ECHO combine in a successful method of explanatory coherence that enables researchers to make judgments of the best of competing explanatory theories. Thagard (1992) is the definitive source for a detailed explication of the theory of explanatory coherence.

Psychology is replete with competing theories that might usefully be evaluated with respect to their explanatory coherence. Durrant and Haig (2001) hinted at how two competing theories of language evolution might be judged in terms of their explanatory coherence. However, examples of the full use of TEC to appraise the best of competing explanatory theories in the behavioral sciences have yet to be provided.

## Research Problems

A number of authors (e.g., Haig, 1987; Laudan, 1977; Nickles, 1981) have stressed the value of viewing scientific inquiry as a problem-solving endeavor. It will be recalled that the overview of ATOM indicated the method's commitment to the notion of a research problem. This acknowledgment of the importance of research problems for inquiry contrasts with the orthodox inductive and hypothetico-deductive accounts of method, neither of which speaks of problem solving as an essential part of its characterization.

In an effort to depict scientific inquiry as a problem-solving endeavor, ATOM uses a *constraint-inclusion* view of research problems (Haig, 1987; Nickles, 1981). The idea of problems as constraints has been taken from the problem-solving literature in cognitive psychology (Simon, 1977) and groomed for a methodological role. Briefly, the constraint-inclusion theory depicts a research problem as comprising all the constraints on the solution to that problem, along with the demand that the solution be found. With the constraint-inclusion theory, the constraints do not lie outside the problem but are constitutive of the problem itself; they actually serve to characterize the problem and give it structure. The explicit demand that the solution be found is prompted by a consideration of the aims of the research, the pursuit of which is intended to fill the outstanding gaps in the problem's structure.

Note that all relevant constraints are included in a problem's formulation. This is because each constraint contributes to a characterization of the problem by helping to rule out some solutions as inadmissible. However, at any one time, only a manageable subset of the problem's constraints will be relevant to the specific research task at hand. Also, by including all the constraints in the problem's articulation, the problem enables the researcher to direct inquiry effectively by pointing the way to its own solution. In a very real sense, stating the problem is half the solution!

The constraint-inclusion account of problems stresses the fact that in good scientific research, problems typically evolve from an ill-structured state and eventually attain a degree of well-formedness such that their solution becomes possible. From the constraint-inclusion perspective, a prob-

[9] In the principles of symmetry and competition, *p* and *q* are to be understood as propositions (hypotheses or evidence statements) within a theory (system of propositions).

[10] The spelling of *Harmany* is deliberate, being a tribute to Gilbert Harman (1965), who coined the term *inference to the best explanation* and introduced the corresponding idea to modern philosophy.

lem will be ill-structured to the extent that it lacks the constraints required for its solution. Because the most important research problems will be decidedly ill-structured, we can say of scientific inquiry that its basic purpose is to better structure our research problems by building in the various required constraints as our research proceeds. It should be emphasized that the problems dimension of ATOM is not a temporal phase to be dealt with by the researcher before moving on to other phases such as observing and hypothesizing. Instead, the researcher deals with scientific problems all the time; problems are generated, selected for consideration, developed, and modified in the course of inquiry.

Across the various research phases of ATOM there will be numerous problems of varying degrees of specificity to articulate and solve. For example, the successful detection of an empirical phenomenon produces an important new constraint on the subsequent explanatory efforts devised to understand that constraint; until the relevant phenomenon, or phenomena, are detected, one will not really know what the explanatory problem is. Of course, constraints abound in theory construction. For example, constraints that regulate the abductive generation of new theories will include methodological guides (e.g., give preference to theories that are simpler, and that have greater explanatory breadth), aim-oriented guides (e.g., theories must be of an explanatory kind that appeals to latent causal mechanisms), and metaphysical principles (e.g., social psychological theories must acknowledge humankind's essential rule-governed nature).

The importance of research problems, viewed as sets of constraints, is that they function as the "range riders" of inquiry that provide ATOM with the operation force to guide inquiry. The constraints themselves comprise relevant substantive knowledge as well as heuristics, rules, and principles. Thus, the constraint inclusion account of problems serves as a vehicle for bringing relevant background knowledge to bear on the various research tasks subsumed by ATOM.

## ATOM and Scientific Methodology

Before concluding the article, I want to identify and briefly discuss two important methodological ideas that are part of the deep structure of ATOM. These ideas are presented in two contrasts: (a) generative and consequentialist methodology and (b) reliabilist and coherentist justification.

### *Generative and Consequentialist Methodology*

Modern scientific methodology promotes two different research strategies that can lead to justified knowledge claims. These are known as *consequentialist* and *generative* strategies (Nickles, 1987). *Consequentialist strategies* justify knowledge claims by focusing on their consequences. By contrast, *generative strategies* justify knowledge claims in terms of the processes that produce them. Although consequentialist strategies are used and promoted more widely in contemporary science, both types of strategy are required in an adequate conception of research methodology. Two important features of ATOM are that it is underwritten by a methodology that promotes both generative and consequentialist research strategies in the detection of phenomena, and generative research strategies in the construction of explanatory theories.

Consequentialist reasoning receives a heavy emphasis in behavioral science research through use of the hypothetico-deductive method, and null hypothesis significance testing, and structural equation modeling within it. Consequentialist methods reason from the knowledge claims in question to their testable consequences. As such, they confer a retrospective justification on the theories they seek to confirm.

In contrast to consequentialist methods, generative methods reason from warranted premises to an acceptance of the knowledge claims in question. Exploratory factor analysis is a good example of a method of generative justification. It affords researchers generative justifications by helping them reason forward from established correlational data patterns to the rudimentary explanatory theories that the method generates. As noted earlier, it is judgments of initial plausibility that constitute the generative justifications afforded by exploratory factor analysis. Generative justifications are forward looking because they are concerned with heuristic appraisals of the prospective worth of theories.

### *Reliabilist and Coherentist Justification*

In addition to embracing both generative and consequentialist methodologies, ATOM uses two different theories of justification, although it does so in a complementary way. These approaches to justification are known as *reliabilism* and *coherentism. Reliabilism* asserts that a belief is justified to the extent that it is acquired by reliable processes or methods (e.g., Goldman, 1986). For example, under appropriate conditions, beliefs produced by perception, verbal reports of mental processes, and even sound argumentation can all be justified by the reliable processes of their production. ATOM makes heavy use of reliability judgments because they furnish the appropriate type of justification for claims about empirical phenomena.[11] For example, as noted earlier, statistical resampling methods such as the bootstrap, and the strategy of constructive replication, are different sorts of consistency tests through which researchers seek to establish claims that data provide reliable evidence for the existence of phenomena.

[11] The use of reliability as a mode of justification, or validation, differs from the normal psychometric practice in which reliability and validity are presented as contrasts. However, the use of consistency tests to validate knowledge claims on reliabilist grounds is widespread in science.

By contrast with reliabilism, *coherentism* maintains that a belief is justified in virtue of its coherence with other accepted beliefs. One prominent version of coherentism, explanationism, asserts that coherence is determined by explanatory relations and that all justification aims at maximizing the explanatory coherence of belief systems (Lycan, 1988). However, the claim that all justification is concerned with explanatory coherence is too extreme, as the existence of reliabilist justification makes clear.

It should be emphasized that, although reliabilism and explanationism are different and are often presented as rivals, they do not have to be seen as competing theories of justification. ATOM adopts a broadly coherentist perspective on justification that accommodates both reliabilism and explanationism and allows for their coexistence, complementarity, and interaction. It encourages researchers first to seek and accept knowledge claims about empirical phenomena based solely on reliabilist grounds, and then to proceed to construct theories that will explain coherently those claims about phenomena. Thus, when using TEC, one is concerned with delivering judgments of explanatory coherence, but TEC's principle of data priority presupposes that the relevant empirical generalizations have been justified on reliabilist grounds.

Further, the acceptability of the claims about phenomena will be enhanced when they coherently enter into the explanatory relations that contain them. Alternatively, the explanatory coherence, specifically the explanatory breadth, of a theory will be reduced as a consequence of rejecting a claim about a relevant phenomenon that was initially accepted on insufficient reliabilist grounds.

## Discussion and Conclusion

This concluding section of the article briefly comments on the nature and limits of ATOM and its implications for research practice. In doing so, it also makes some remarks about the nature of science.

### *Phenomena Detection and Theory Construction Again*

Recognition of the fundamental importance of the distinction between empirical phenomena and explanatory theory suggests the need to differentiate between empirical progress and theoretical progress in science. The successful detection of a phenomenon is a major achievement in its own right, and it is a significant indicator of empirical progress in science. (The importance of phenomena detection in science is underscored by the fact that more Nobel prizes are awarded for the discovery of phenomena than for the construction of explanatory theories.) From the perspective of ATOM, theoretical progress is to be understood in terms of the goodness of explanatory theories as determined by TEC. Arguably, behavioral science methodology has placed a heavier professional emphasis on the description of empirical regularities than on the construction of explanatory theories. However, ATOM takes phenomena detection and theory construction to be of equal worth.

The characterization of phenomena given earlier in the article helps correct two widely held misunderstandings of science. First, it makes clear that taking the distinction between observation and theory to be of fundamental methodological importance prevents one from being able to conceptualize properly the process of phenomena detection. This holds whether or not one subscribes to a hard-and-fast observation–theory distinction, or whether one accepts a relative observation–theory distinction and the ambiguous idea of theory ladenness that goes with it. To correctly understand the process of phenomena detection, one needs to replace the observation–theory distinction with the threefold distinction between data, phenomena, and theory.

This suggested replacement also serves to combat the tendency to overemphasize the importance of observation as a source of evidence in science. For it is phenomena, not data, that typically serve as evidence for theories. Moreover, although data serve as evidence for phenomena, their perceptual qualities in this role are of secondary importance. Methodologically speaking, what matters in science is not the phenomenal or experiential qualities of perception but whether or not perception is a reliable process (Woodward, 1989). It is for this reason that reliable nonhuman measurement techniques are just as important as human perceptual techniques in detecting phenomena.

Generally speaking, the implications of ATOM's account of phenomena detection for research practice in the behavioral sciences is consistent with a number of recent proposals for improving researchers' data analytic practices. In particular, the model of data analysis outlined in this article reinforces the importance now accorded exploratory data analysis in psychology (Behrens & Yu, 2003). In addition, it highlights the need to recognize that computer-intensive resampling methods are a valuable source of pattern confirmation—a point oddly ignored by the American Psychological Association's Task Force on Statistical Inference (Wilkinson & the Task Force on Statistical Inference, 1999). Of interest, at a general level, the acknowledgment of phenomena detection as a distinctive research undertaking in its own right enables behavioral scientists to endorse the inductivism of radical behaviorist methodology but eschew its instrumentalist prescriptions for theorizing and postulate latent causal mechanisms instead. This constructive part of radical behaviorism is an account of phenomena detection that can be found in the biological sciences (Sidman, 1960). As such, it deserves a wider adoption in the behavioral sciences than is currently the case.

ATOM's account of theory construction is at variance with the way many behavioral scientists understand theory construction in science. Most behavioral scientists probably use, or at least endorse, a view of theory construction that is strongly shaped by the guess-and-test strategy of the hypothetico-deductive method. In contrast with this prevailing conception of scientific method, ATOM asserts that (a) theory generation can be a logical, or rational, affair, where the logic takes the form of abductive reasoning; (b) theory development is an important part of theory construction—an undertaking that is stifled by an insistence on immediate testing; and (c) empirical adequacy, understood as predictive success, is not by itself an adequate measure of theory goodness, there being a need to use additional virtues to do with explanatory worth.

ATOM's three phases of theory construction have varying degrees of application in the behavioral sciences. Codified methods that generate theories through existential abduction are rare. The use of exploratory factor analysis to postulate common causes is a striking exception, although the explicit use of this method as an abductive generator of elementary plausible theory is rarely acknowledged. Grounded theory method (Strauss, 1987), which is increasingly used in behavioral research, can be regarded as an abductive method that helps generate theories that explain the qualitative data patterns from which they are derived. However, it does not confine itself to existential abduction, and it imposes weaker constraints on the abductive reasoning permitted by the researcher than does exploratory factor analysis. The earlier suggestion that as human beings, we have an evolved cognitive ability to abductively generate hypotheses leads to the plausible suggestion that scientists frequently reason to explanatory hypotheses without using codified methods to do so. Two prominent examples in the behavioral sciences are Chomsky's (1972) publicly acknowledged abductive inference to his innateness hypothesis about universal grammar, and Howard Gardner's (Walters & Gardner, 1986) self-described use of "subjective factor analysis" to postulate his multiple intelligences. Also, it is likely that behavioral scientists use some of the many heuristics for creative hypothesis generation listed by McGuire (1997) in order to facilitate their abductive reasoning to hypotheses.

The strategy of analogical modeling is sometimes used in the various behavioral sciences to develop theories. This is not surprising, given that many of the proposed causal mechanisms in these sciences are theoretical entities whose natures can only be got at indirectly using such a modeling strategy. However, there is little evidence that the behavioral sciences explicitly incorporate such a strategy into their methodology and their science education practices. Given the importance of such a strategy for the expansion of explanatory theories, methodologists in the behavioral sciences need to promote analogical modeling as vigorously as they have promoted structural equation modeling. Structural equation modeling provides knowledge of causal networks. As such, it does not so much encourage the development of detailed knowledge of the nature of the latent variables as it specifies the range and order of causal relations into which such variables enter. By contrast, analogical modeling seeks to provide more detailed knowledge of the causal mechanisms by enumerating their components and activities. These different forms of knowledge are complementary.

Inference to the best explanation is an important approach to theory appraisal that has not been explicitly tried in the behavioral sciences. Instead, hypothetico-deductive testing for the predictive success of hypotheses and theories holds sway. TEC, which is the only codified method of inference to the best explanation, can be widely used in those domains where there are two or more reasonably well-developed theories that provide candidate explanations of relevant phenomena. By acknowledging the centrality of explanation in science, one can use TEC to appraise theories with respect to their explanatory goodness. It is to be hoped that behavioral science education will soon add TEC to its concern with cutting-edge research methods.

### *The Scope of ATOM*

Although ATOM is a broad theory of scientific method, it should not be understood as a fully comprehensive account. ATOM is a singular account of method that is appropriate for the detection of empirical phenomena and the subsequent construction of postulational theories, where those theories purportedly refer to hidden causal mechanisms, and where their causes are initially given a rudimentary, dispositional characterization. However, in dealing with explanatory theories in which the causal mechanisms referred to are more directly accessible than theoretical entities, researchers do not have to use a strategy of analogical modeling in order to provide a more informative characterization of their theories. The use of functional brain imaging techniques, such as functional magnetic resonance imaging, in order to map neuronal activity in the brain is a case in point. Further, although the evaluation of theories in terms of explanatory criteria deserves a heavy weighting in science, inference to the best explanation will not always be an appropriate, or a sufficient, resource for evaluating theories. For example, although predictive success has probably been overemphasized in both scientific methodology and practice (Brush, 1995), it nevertheless remains an important criterion of a theory's worth. It, may, therefore, be sought in a modified hypothetico-deductive strategy that corrects for the confirmational inadequacies of its simple form.

Like all theories of scientific method, ATOM is normative in the sense that it advises researchers of what to do in a limited number of research contexts. However, it is important to stress that the normative force of ATOM is conditional in nature. More precisely, its recommendations are subjunctive conditionals that take the form "If you want to reach goal *X*, then use strategy *Y*." The justification for pursuing goal *X* rests with the researcher; it is not to be found in ATOM. Laudan (1996) argued in detail for the conditional nature of methodological recommendations, and Proctor and Capaldi (2001) recently commended his view of methodology to psychologists.

### Conclusion

ATOM aspires to be a coherent theory that brings together a number of different research methods and strategies that are normally considered separately. The account of phenomena detection offered is a systematic reconstruction of a practice that is common in science but that is seldom presented as a whole in methodological writings. The abductive depiction of theory construction endeavors to make coordinated sense of the way in which science sometimes comes to obtain knowledge about the causal mechanisms that figure centrally in the understanding of the phenomena that they produce. With rare exceptions, the abductive generation of elementary plausible theory, the strategy of analogical modeling, and the method of inference to the best explanation are all yet to receive explicit consideration in psychology and the other behavioral sciences—but see Rozeboom (1999), Harré and Secord (1972), and Eflin and Kite (1996), respectively. ATOM serves to combine these methodological resources in a broad theory of scientific method.

The question of whether ATOM is a genuinely coherent theory of method remains to be answered. Although it is a fairly comprehensive account of method, and although it seems to capture a natural order of scientific inquiry, further development is required before its cohesiveness can be properly judged. My hope is that, upon fuller explication, ATOM might be shown in a reflexive way to be an explanatorily coherent theory of scientific method.

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