Crafting Theory to Satisfy the Requirements of Explanation

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Abstract

Positivism, in defining what it means by "explanation," leads to certain requirements for theory to satisfy. We refer to explanation as defined in the positivist philosopher Carl G. Hempel's deductive-nomological model of explanation. The requirements pertain to the operationalization of a theory, the precision with which a theory needs to be stated, and the composition of a theory. Researchers who consider themselves positivist need to craft their theories to satisfy these requirements. Counterintuitive findings are that the rigor of an explanation and the theory it uses is independent of whether or not they involve statistical analysis, that mathematical operationalizations of behavioral theories suffer from underdetermination, and that qualitative research can live up to the requirements of positivist explanation.

1. Introduction

What is explanation? What is a rigorous model of explanation? How can theory in information-systems research live up to the requirements of a rigorous model of explanation?

To address these questions, we take a positivist approach. We do this for three reasons. First, much, if not most, information-systems research is positivist. We seek to address positivist information-systems researchers in this essay. The second is that the positivist model of explanation that we will adopt – the deductive-nomological model [7] – is clearly defined, and can therefore provide a clear point of comparison for other, non-positivist perspectives in any future discussions on the requirements of explanation for theory. The third reason is that information-systems researchers who profess to be positivist need to live up to the requirements of positivism, including positivism's requirements for what constitutes an explanation. We pose those requirements in this essay and challenge positivist researchers to live up to them.

The gist of this essay is that "theory" is a human-made artifact, one that researchers can and must craft in order to satisfy certain requirements, including the requirements for what a rigorous explanation is.

The next, second section of this essay will offer, by way of introduction, some general definitions of explanation as well as present positivism's formal, deductive-nomological model of explanation. The second section will illustrate the deductive-nomological model of explanation with a natural-science example. A natural-science example is salient in so far as positivism originated as a philosophy of natural science and, as part of that philosophy, regarded natural-science inquiry as providing the archetype for social-science inquiry. Then, to show how the deductive-nomological model of explanation applies in social science, the third section will provide a behavioral-research example from positivist information-systems research. It is the technology acceptance model in its original form, as offered by Davis, Bagozzi, and Warshaw [4]. The fourth section will formulate, from the natural-science example and the behavioral-research example, the requirements that theory needs to satisfy for a researcher to be able to use it in order to provide an explanation of a phenomenon, at least according to positivism. The final section will identify ramifications for how positivist information-systems research should be done, in light of the requirements that a rigorous model of explanation imposes on theory.

2. Descriptions of Explanation

By way of introduction, for some general notions about what "explanation" might mean, we turn to some popularly used dictionaries. According to the *Oxford Dictionary of English* [5], "explanation" means "a statement or account that makes something clear" or "a reason or justification given for an action or belief." According to the *Merriam-Webster Dictionary* [1], "explain" means, among other things, "to make known," "to make plain or understandable," and "to give the reason for or cause of," where "explanation" means "the action or process of explaining." According to *Dictionary.com* [6], "explain" can mean "to make plain or clear; render understandable or intelligible," "to make known in detail," "to assign a meaning to; interpret," and "to make clear the cause or reason of; account for," where "explanation" can mean

"the act or process of explaining," "something that explains; a statement made to clarify something and make it understandable; exposition," "a meaning or interpretation," and "a mutual declaration of the meaning of words spoken, actions, motives, etc., with a view to adjusting a misunderstanding or reconciling differences."

Explanation in academic research can be consistent with its lay definitions; however, at the same time, it needs to address any additional requirements of the given academic specialty. For positivist information-systems research, we turn to the requirements imposed by the deductive-nomological model of explanation, whose origin is credited to the positivist philosopher of science, Carl G. Hempel [7]. We adopt the basics on which Hempel built his positivist model, which include certain logical tools (such as the logic of the syllogism) and certain empirical tools (such as observation-based experimentation). We use the term "basics" because these logical and empirical tools were already in existence prior to the rise of positivist philosophy. Furthermore, we may properly rely on these basics in so far as they have survived, retaining their legitimacy, even after the demise of positivist philosophy.

In the following discussion, we focus on explanation as the explanation *of a phenomenon*, where a phenomenon is defined as "a fact or situation that is observed to exist or happen, especially one whose cause or explanation is in question" [5]. In the sort of explanation embodied in the deductive-nomological model, our concern is: What general principles (e.g., what scientific law or theory) and what initial conditions (e.g., what circumstances) can account for the resulting observed fact or situation? Following Hempel [7], Rosenberg [13, pp. 23-33] points out that, in the deductive-nomological model of explanation, statements of the general principles and initial conditions make up the **explanans**, which he calls *the sentences in an explanation that do the explaining*. Rosenberg also notes that statements of the observed fact or situation make up the **explanandum**, which he calls *the sentences that report the fact or situation to be explained*.

More formally, the deductive-nomological model is defined as taking the form of what symbolic logic considers to be a valid deductive argument. A valid deductive argument is a syllogism, which is made up of a major premise, a minor premise, and a conclusion.

The major premise in the deductive-nomological model of explanation consists of statements of a scientific law or theory, which play the role of the aforementioned general principles. The researcher

Table 1

An Example of an Explanation as a Valid Deductive Argument, Using the Logic of the Syllogism

the explanans				
"sentences in an explanation which do the explaining" (Rosenberg, p. 26)	major premise	general statements offered to explain a phenomenon	Chosen here for illustrative purposes, this equation shows force as a function of velocity.	$F = \beta_0 + \beta_1 V + \beta_2 V^2$
	minor premise	particular statements that describe an occurrence of the phenomenon; the "initial conditions" (Rosenberg, p. 26)	A particular situation involves a certain "object as it undergoes a vertical free fall through a given fluid." There are 18 measurements of the velocity (meters/second) and associated force (newtons).	V F V F 0.00 5.00 4.50 3.74 0.50 4.94 5.00 3.50 1.00 4.86 5.50 3.24 1.50 4.76 6.00 2.96 2.00 4.64 6.50 2.66 2.50 4.50 7.00 2.34 3.00 4.34 7.50 2.00 3.50 4.16 8.00 1.64 4.00 3.96 8.50 1.26
the explanandum	conclusion	instantiation of the general statements for this occurrence of the phenomenon, where they describe what is the cause of, is the antecedent of, or is correlated with the observed outcomes	This equation results from applying the major premise to the minor premise. "$F = 5.00 - 0.10 V - 0.04 V^2$" is an instantiation of "$F = \beta_0 + \beta_1 V + \beta_2 V^2$."	$F = 5.00 - 0.10\,V - 0.04\,V^2$
sentences "which report the event to be explained" (Rosenberg, p. 26)				

who puts forth these statements intends them to be invariant across different situations (e.g., different populations, different field sites, different laboratory experiments) where different instances of the phenomenon can be observed. These statements may, but need not, be expressed as a set of equations.

The minor premise consists of statements of the aforementioned initial conditions, which can take the form of numerical measurements of the observed instance of the phenomenon. They vary from one instance of the phenomenon to another – for instance, from one population to another, from one field site to another, from one laboratory experiment to another.

The conclusion, the last part of the syllogism, logically and necessarily follows from applying the major premise to the minor premise. The conclusion is, as we will illustrate, the scientific law or theory in the form it takes when calibrated to fit the observed phenomenon.

Our foregoing presentation of the deductive-nomological model of explanation has been deliberately general and abstract, including its presentation of the concepts of "valid deductive argument," "syllogism," "major premise," "minor premise," "conclusion," "explanans," and "explanandum." We now provide concrete illustrations of the deductive-nomological model of explanation, including these concepts, with a natural-science example and a behavioral-research example.

3. First Example of Explanation: from Natural Science

We purposely select for our first illustration (summarized in Table 1, above) an example from natural science. This is appropriate and helpful because the very concepts of theory and explanation, as used in the positivist social sciences, originated in the natural sciences, and the natural-science meanings and connotations of these terms continue to influence those social scientists who call themselves positivist. Also, a natural-science case offers a "clean" example, not complicated by how the social sciences are different from the natural sciences – which is an important consideration in the presentation of concepts originating in the natural sciences.

Table 1 presents a natural-science (physics) example consisting of a major premise, minor premise, and conclusion. In this example, adapted from [18], the phenomenon that we seek to explain is the force exerted by an object that is undergoing a vertical free fall in a fluid. The major premise consists of the general statement "$F = \beta_0 + \beta_1 V + \beta_2 V^2$," which theorizes the relationship between the velocity of the

object, V, and the force exerted by the object, F. Each β_i is a constant. We use "$F = \beta_0 + \beta_1 V + \beta_2 V^2$" as the major premise in the first row in Table 1.

The minor premise in this example is measurements that we make, in a single laboratory setting, of the particular object that we observe undergoing a vertical free fall in a particular fluid. The minor premise takes the form of 18 measurements of the force F and the velocity V for this particular object. Where each data point i is (v_i, f_i,), the initial conditions are (0.00, 5.00), (0.50, 4.94), (1.00, 4.86), … , (8.50, 1.26) for i = 1, 2, 3, … , 18. The minor premise is the second row in Table 1.

The conclusion, containing the "fitted" theory, takes the form of the equation "$F = 5.00 - 0.10\ V - 0.04\ V^2$." We call it "fitted" because its parameters (β_0, β_1, and β_2) have been calibrated to fit the given, observed object for which the 18 measurements were taken. The conclusion "$F = 5.00 - 0.10\ V - 0.04\ V^2$" appears in the third row of Table 1 and, as the explanandum, can be said to report the force f_i exerted by this object in its free fall.

In general, in the deductive-nomological model of explanation, an explanation consists of not only the scientific law or theory, but the law or theory (as the major premise in a valid deductive argument) in conjunction with both the initial conditions (the deductive argument's minor premise) and the resulting report consisting of the law or theory as applied to the initial conditions (the deductive argument's conclusion which, in our example, is the fitted equation). Together, the theory and the initial conditions fill the role of *the sentences in an explanation which do the explaining* (the **explanans**) and, in our example, the fitted equation fills the role of *the sentences that report the situation to be explained* (the **explanandum**), which is the force exerted by the particular object that we observe undergoing a vertical free fall in the particular fluid in our laboratory setting.

It is worth noting that, in Table 1, "$F = \beta_0 + \beta_1 V + \beta_2 V^2$" is a theory rather than a scientific law. The difference between a theory and a law is important for the following reasons. Laws are taken to be true whereas theories, by definition, are theoretical and require empirical testing to determine if they may be considered true. Indeed, one of the definitions of the term "nomological" is "relating to or denoting certain principles, such as laws of nature, that are neither logically necessary nor theoretically explicable, but are simply taken as true" [17]. However, when one inserts a theory, rather than a law, into the major premise of the deductive-nomological model of explanation, the consequent explanandum (e.g., the fitted equations in the syllogism's conclusion) is no longer just an empirical report of an observed instance of a

phenomenon, but also a source of predictions of what a person (e.g., a researcher conducting an experiment) should observe in this instance if the theory is true. For example, for the object being observed in the laboratory, what would one predict this object's force to be for a velocity not included among the 18 data points that were collected? Such predictions, computed from the fitted equation "$F = 5.00 - 0.10 V - 0.04 V^2$," would be instances of what the philosophy of science has called the "observational consequences" of a theory.

Therefore, in the example in Table 1, because "$F = \beta_0 + \beta_1 V + \beta_2 V^2$" in the explanans is a theory rather than a law, then "$F = 5.00 - 0.10 V - 0.04 V^2$" in the explanandum, despite being a logical conclusion following from the major and minor premises, would be seen not as conclusive, but instead as empirically refutable. For the observed object for which the theory was calibrated to fit the initial conditions, the theory would only hypothesize the force f_i for a given velocity v_i. In other words, every different velocity v_i (not just those included in the initial conditions) allows a force f_i to be predicted from the equation in the explanandum, and then to be compared to a measurement of the object's actual force observed in an experiment. Until and unless such comparisons are made in an experiment, it is literally only a theory that a predicted value will match the observed and measured value for data points outside the original 18 in the initial conditions. In general (i.e., not just for our example in Table 1), a theory (in the role of the syllogism's major premise, in the explanans) needs to be empirically tested through its predictions or observational consequences (which follow from the syllogism's conclusion, the explanandum).

Such testing would entail a separate and subsequent application of a different syllogism, taking the form of *modus tollens* [11] where its major premise would be "if the theory is true, then a prediction derived from it is true"; its minor premise, "this prediction is not true"; and its conclusion, "therefore, the theory is not true." In the case of the example in Table 1, the explanandum in the third row allows numerous (even infinite) such predictions to be derived and then tested against observation (i.e., every new value for V will result in a new, predicted value for F), where each new prediction poses an opportunity for the theory to survive an empirical test. According to the tight logic of *modus tollens*, the absence of failed predictions is a necessary condition for a theory to be considered true, where the absence of failed predictions is always just a tentative status, open to being revised in accordance with the results of continued testing.

Strictly speaking, such empirical testing is properly described as not being a part of a deductive-nomological explanation, but instead as being made possible by, and taking place subsequent to, the formulation of a deductive-nomological explanation.

A surprising point worth emphasizing is that *statistical methodology is not necessary to explanation and is therefore not a part of the definition of explanation.* We note that the example in Table 1 involves no statistical inference in general and no statistical hypothesis testing in particular. Indeed, if statistical estimation methods had been applied in this example, they would have been completely superfluous. A statistical estimation method for fitting the general statement "$F = \beta_0 + \beta_1 V + \beta_2 V^2$" to the given 18 data points would have resulted in an r-square of 1 (because the equation fits the data perfectly) and, accordingly, the measured values of the coefficients β_1 and β_2 would have both enjoyed excellent (if not perfect) levels of statistical significance.

What, then, is the role of statistical methodology? We will examine this later in the discussion on the second example, which involves a behavioral-research example.

Because our adaptation of the deductive-nomological model of explanation is no longer nomological (i.e., we are adapting this model, originally intended for scientific laws or what Hempel called "covering laws," to scientific theories), we adjust its name to the explanans-explanandum model of explanation. More than just a change in name, it also involves a change in meaning and function. The change in meaning is that the original syllogism's conclusion, the explanandum, is no longer a conclusive report. The change in function is that the explanandum serves as the source of predictions that are subsequently tested through another syllogism, *modus tollens*, which had no role or presence in, but is applied subsequent to, the formulation of the deductive-nomological explanation.

In the foregoing discussion, a theory itself is not an explanation and does not provide an explanation, but plays a role in providing an explanation. A theory plays the role of the major premise, which is part of the explanans, where the explanans and the explanandum together make up the explanation.

Table 2				
An Example of an Explanation as a Valid Deductive Argument, Using the Logic of the Syllogism				
the explanans "sentences in an explanation which do the explaining" (Rosenberg, p. 26)	major premise	general statements offered to explain a phenomenon	Chosen here for illustrative purposes, these statements refer to the technology acceptance model, mathematically operationalized in the form of three equations.	$BI = \beta_{1,0} + \beta_{1,1}A + \beta_{1,2}U$ $A = \beta_{2,0} + \beta_{2,2}U + \beta_{2,3}EOU$ $U = \beta_{3,0} + \beta_{3,3}EOU$
	minor premise	particular statements that describe an occurrence of the phenomenon; the "initial conditions" (Rosenberg, p. 26)	The datum 1.9 in this table has the meaning that BI=1.9, where i=2 refers to the second person for whom measurements are taken. The table presents measurements for 250 people in an occurrence of the phenomenon that the general statements are offered to explain.	<table><tr><td></td><td>BI</td><td>A</td><td>U</td><td>EOU</td></tr><tr><td>i=1</td><td>2.1</td><td>1.0</td><td>4.1</td><td>4.7</td></tr><tr><td>i=2</td><td>1.9</td><td>1.7</td><td>3.7</td><td>3.4</td></tr><tr><td>...</td><td>...</td><td>...</td><td>...</td><td>...</td></tr><tr><td>i=250</td><td>2.0</td><td>3.1</td><td>2.4</td><td>4.8</td></tr></table>
the explanandum sentences "which report the event to be explained" (Rosenberg, p. 26)	conclusion	instantiation of the general statements for this occurrence of the phenomenon, where they describe what is the cause of, is the antecedent of, or is correlated with the observed outcomes	These three equations result from applying the major premise to the minor premise. "BI = 2.8 + 0.4 A + 1.8 U" is an instantiation of "BI = $\beta_{1,0}$ + $\beta_{1,1}$ A + $\beta_{1,2}$ U." The other two equations can be described correspondingly.	$BI = 2.8 + 0.4\,A + 1.8\,U$ $A = 1.7 + 2.0\,U + 0.8\,EOU$ $U = 0.7 + 1.2\,EOU$

Can a behavioral-research theory, such as those in information-systems research, play the same role that a natural-science law or theory plays in explanation, especially in the particularly rigorous explanans-explanandum model of explanation? In other words, if a researcher – especially, an information-systems researcher – were aware, prior to formulating his or her theory, that the theory would need to play a role in the explanans-explanandum model of explanation, what requirements would the researcher need to craft the theory to satisfy? We will address these questions after examining the example in Table 2 (below).

4. Second Example of Explanation: from Behavioral Research

The example in Table 2 uses Davis *et al.*'s [4] original form of the technology acceptance model or "TAM" as a theory, and operationalizes it in the form of three equations. Davis *et al.* present the theory in narrative form, using statements such as the following:

> TAM postulates that computer usage is determined by BI [a person's behavioral intention to use the technology], but differs [from the theory of reasoned action] in that BI is viewed as being jointly determined by the person's attitude toward using the system (A) and perceived usefulness (U) [p. 985].

> According to TAM, A is jointly determined by U and EOU [the person's perceived ease of use of the technology] [p. 986].

> To the extent that increased EOU contributes to improved performance, as would be expected, EOU would have a direct effect on U [p. 987].

Davis *et al.* offer a mathematical operationalization of the foregoing verbal statements in the form of three equations. We offer a mathematically equivalent restatement of them in Table 2's first row as the following, where they make up the major premise:

$$BI = \beta_{1,0} + \beta_{1,1}A + \beta_{1,2}U$$
$$A = \beta_{2,0} + \beta_{2,2}U + \beta_{2,3}EOU$$
$$U = \beta_{3,0} + \beta_{3,3}EOU$$

Next, suppose that the minor premise, containing the initial conditions, consists of measurements of 250 data points (250 persons), each one referring to 4 mathematical variables (BI, A, U, and EOU) and assigning a numerical value to each of them. These data appear in the second row of Table 2. A behavioral researcher who does statistical research would recognize these data as associated with a random sample taken from a population. For the sake of argument, we presume that these data satisfy assumptions required for statistical inference to proceed.

The conclusion, appearing in the third row of Table 1 and resulting from applying the major premise to the minor premise, consists of three fitted equations:

$$BI = 2.8 + 0.4\ A + 1.8\ U$$
$$A\ = 1.7 + 2.0\ U + 0.8\ EOU$$
$$U\ = 0.7 + 1.2\ EOU$$

These fitted equations are instantiations of the original general equations. The fitted equations are the specific form taken by the original equations after the latter have been transformed to fit the given population, using the sample data taken from the population. As the explanandum, the three fitted equations report (for the average individual in the statistical experiment in which a sample of size 250 was taken) the individual's behavioral intention to use the new technology, in exactly the same way as the earlier fitted equation "$F = 5.00 - 0.10\ V - 0.04\ V^2$" reports (for the object observed in a vertical free fall in a fluid for which the 18 measurements were taken) the object's force.

There is at least one major difference, however, between the current behavioral-research example and the earlier natural-science example. Typically in behavioral research, the fit between the equations and the data in the initial conditions is hardly as good as in natural science. Indeed, the natural-science example in Table 1 involves 18 data points that fit the equation perfectly. Statistical estimation procedures, including statistical hypothesis testing, then come into play in situations where the fit is hardly perfect (indeed, in the social sciences, a commonly used measure of fit, "r-square," is often considered acceptable even if it is as low as .20 or 20%, where it would be 1.00 or 100% for a perfect fit); in such situations, there is a need to calibrate numerical estimates for the β_i coefficients so as to provide the best fit possible between the equation(s) in the major premise and the data in the minor premise.

We emphasize that even in this situation, however, statistical methods do not drive an explanation. They merely provide calibration (i.e., they calibrate the values of the β_i coefficients so that the equations will fit the data as closely as possible). And even if the fit were perfect (i.e., the situation in which the r-square value for the fitted equation is 1.00 and the levels of statistical significance for the numerical estimates for the β_i coefficients are all $p<.001$), this would merely return us to the same situation we discussed previously where the major premise is a theory and not a law: It is the situation where the empirical testing of the theory through its predictions would nonetheless have to proceed. The need for such testing in behavioral research has already been recognized by Lee and Hubona [11], who devised a procedure that applies the logic of *modus tollens* and computes the level of statistical significance associated with the percentage of the tested predictions that are failed predictions. In their study, Lee and Hubona conduct empirical tests of predictions made by TAM and, using this procedure, are able to make decisions to reject the hypothesis that TAM is true where the decisions are made at statistically significant levels.

We also emphasize that the theory, TAM, is not probabilistic, inductive, or statistical, but is expressed by Davis *et al.* as a set of deterministic mathematical equations. It is not the theory, but its particular operationalization, that has probabilistic, inductive, and statistical elements. This is the case for many or even most theories in behavioral information-systems research.

5. Requirements of Positivist Explanation for Theory to Satisfy

If a positivist information-systems researcher were to develop or craft a theory so that, among other things, it would fit the explanans-explanandum model of explanation, what requirements would the theory need to satisfy?

We offer three interrelated requirements: First, the formulation of the theory must be sufficiently tight so that its operationalization appearing in the major premise would allow the theory to be empirically refuted; second, the theory must be stated either in terms of symbolic logic or in terms that are as unambiguous as those of symbolic logic; and third, the composition of the theory may include what symbolic logic considers to be statement variables and individual variables, but not statement constants and individual constants. Our discussion of the rationale for the first requirement will lead to the rationales for the second and third requirements. The three requirements arise from opening up and examining research assumptions that are normally taken for granted, but that the explanans-explanandum model of explanation lays bare and shows to be problematic in the case of

behavioral research. These problems become apparent in examining differences between the natural-science example in Table 1 and the behavioral-research example in Table 2.

In Table 1, the theory in the natural-science example takes the form of an equation, serving as the major premise. A theory's taking the form of an equation is not always the case in natural science, but is more likely in natural science than in behavioral research. Theories in behavioral research are more often expressed in prose than in mathematics. The operationalization of prose into mathematics (so that quantification and statistical hypothesis testing can take place), however, can involve a loss in translation or other distortion.

A case in point happens to be the behavioral-research example in Table 2, where the equations in the major premise are not the theory, but are a mathematical operationalization of the theory, where Davis *et al.* stated the theory verbally. We have already quoted the three theoretical statements. Davis *et al.* operationalized these theoretical statements mathematically, appearing in Table 2 as:

$$BI = \beta_{1,0} + \beta_{1,1}A + \beta_{1,2}U$$
$$A = \beta_{2,0} + \beta_{2,2}U + \beta_{2,3}EOU$$
$$U = \beta_{3,0} + \beta_{3,3}EOU$$

However, these three equations *are only one possible operationalization of the preceding three theoretical statements*. First, these three equations all involve linear relationships among the variables, *but the theoretical statements do not limit the relationships to only linear ones*. Second, all the variables happen to be continuous, *but the theoretical statements do not limit the variables to only continuous ones*, nor do they require only continuous functions. Third, the three equations also presume a cross-sectional view of the phenomenon, *but the theoretical statements also allow a longitudinal view*. We emphasize that Davis *et al.*'s operationalization is not incorrect. Rather, their operationalization is fine, but other operationalizations would be fine, too. When, then, is the difficulty?

The difficulty is that, in the needed, subsequent empirical testing of the theory through these equations, any refutations of the predictions made by the three equations would refute only these equations, *not the theory*. This is because one could rightly argue that the theory also allows for other operationalizations (e.g., a different set of equations, involving nonlinear relationships among the variables), among which there could be one that, when applied to the initial conditions to yield an explanandum, will lead to predictions that would be consistent with observations. The result in this situation is that the theory need never be considered refuted, even in the face of observations that plainly refute predictions derived from it.

The requirement that a theory be operationally falsifiable is different from the already well known requirement that a theory be logically falsifiable. A theory that is not logically falsifiable, as elucidated by Popper [12], refers to a theory whose logical formulation is so loose that predictions or observational consequences derivable from it can cover even contradictory events (the classic example of such a prediction is, "tomorrow, it will rain or not rain"), hence allowing the theory to evade all attempts at empirical refutation. On the other hand, a theory that lacks operational falsifiability is one that allows such a wide range of operationalizations that any empirical refutation can be attributed to (i.e., blamed on) just the particular operationalization and not the theory, as exemplified in the preceding discussion of the behavioral-research example in Table 2.

In a sense, just as there can be theoretical underdetermination (the problem in which multiple differing theories exist with which to explain the same phenomenon), there can also be what we now call operational underdetermination (the problem in which multiple differing operationalizations exist with which to empirically test the same theory). Thus, our encounter with the rigor of the positivist explanans-explanandum model of explanation compels positivist researchers to confront what the philosophy of science has known as the problem of underdetermination in general [16].

The remedy is to institute **the requirement that the formulation of the theory must be sufficiently tight so that the empirical refutation of any of its operationalizations would also serve as an empirical refutation of theory itself**. This requirement arises from our consideration of the explanans-explanandum model of explanation, whose explanandum is the source of predictions (or "observational consequences") to be tested. In the case of the example in Table 2, what might a tighter formulation involve?

Davis *et al.*'s three theoretical statements are exemplary in actually naming its variables (e.g., BI, A, U, EOU) in so far as not all research studies provide theoretical statements that do this. At the same time, Davis *et al.*'s three theoretical statements also need to specify not only the theory's variables, but also the relationships among the variables. To posit that two variables are "jointly determined," or that one variable would "would have a direct effect on" another, is simply not sufficiently specific. Is the relationship linear? Is the relationship log-linear? Or may the relationship simply be one that is monotonically increasing? Is a given variable necessarily continuous?

Is the theorized relationship longitudinal or cross sectional? For behavioral research in information systems, Davis *et al.*'s theoretical statements follow the norm in not addressing or acknowledging these questions. However, for research that claims to be positivist, positivism's explanans-explanandum model of explanation requires such questions to be addressed in order for a theory to be operationally testable and falsifiable.

This discussion leads naturally to the next requirement, which is that **the theory must be stated either in terms of symbolic logic or in terms that are as unambiguous as those of symbolic logic**. A theory that is already formulated mathematically would require no operationalization to serve as the major premise in the explanans and, therefore, would satisfy this requirement. The case of our natural-science example in Table 1 illustrates this: The theory (regarding the force of an object undering a vertical free fall in a fluid) is already stated in mathematical form ("$F = \beta_0 + \beta_1 V + \beta_2 V^2$"), which is also exactly how it appears in the major premise, so there is no operationalization in which any loss of meaning or other distortion can occur.

However, where the theory is not yet ready for being stated mathematically, or is not suitable in the first place for a mathematical formulation because it involves variables that are not intended to represent numerical values (as in positivist case studies), there already exist some concepts in symbolic logic that can help to provide the needed precision or to avoid unnecessary ambiguity. These symbolic-logic concepts are "individual variable," "individual constant," "statement variable," "statement constant," and "propositional function." Perhaps the most important of these regarding the problem of operational underdetermination is the last one – propositional function. We now proceed to examine each of these concepts.

The words "variable," "constant," and "function" in symbolic logic are more general than, and can subsume, their usage in mathematics. These terms (with some variation, e.g., "statement variable" is synonymous with "categorical sentence") can be found in introductory logic textbooks [3][9]. Burton-Jones and Lee offer this summary [2, p. 1]:

> In the proposition, "if *p* is true, then *q* is true," *p* is a **statement variable** that, like any variable, can take a particular value, such as *all humans are mortal*, where *all humans are mortal* is an example of a **statement constant**. In the same manner, the **statement variable** *q* can take the particular value *Socrates is mortal*, for

which *Socrates is mortal* is an example of a **statement constant**. Finally, *humans* itself is an **individual variable** that takes the particular value *Socrates*, where *Socrates* is an **individual constant**. Note that the adjective "individual" does not necessarily refer to a human individual. "Return on investment" or "ROI" can be an individual variable, for which "7%" could be an individual constant.

We note that Davis *et al.* may be credited for explicitly naming and identifying their variables, BI, A, U, and EOU, which may be regarded equally well as mathematical variables or (in symbolic logic) individual variables. Davis *et al.* are following a typical research convention in not mentioning explicitly any of the numerical values (or the individual constants) that can be assigned to their variables; however, explicitly stating some values as examples or the range that they may take could help the reader of their study better anchor the empirical meaning of their work, especially if the reader is a practitioner.

The remaining symbolic-logic concept, mentioned above, that we still need to define is "propositional function." We define it by analogizing it to a mathematical function. Just as a mathematical function indicates how its mathematical variables are related to one another, *a propositional function indicates how its individual variables are related to one another*. Furthermore, just as a mathematical function will state mathematical variables but not numbers, a propositional function will state individual variables but not individual constants.

In this context, we note again that Davis *et al.*'s theoretical statements need to better specify the relationships among the variables. If the term "propositional function" had existed for Davis *et al.* (and other information-systems researchers), they would have been aware of the need to better specify the relationships among the different individual variables in the narrative presentation of their theory (i.e., to specify the relationships among the variables with terms not as open-ended as "jointly determined" and "have a direct effect on"). It is reasonable to expect that better specifying the relationships among the different individual variables in the narrative presentation of one's theory can subsequently help in better specifying the relationships among the mathematical variables in one's mathematical operationalization of the theory.

Davis *et al.* deserve credit for explicitly stating the equations making up the mathematical operationalization of their theory. Most behavioral-

research articles in information systems do not reveal the equations constituting their statistical model. Still, stating the equations that make up an operationalization is different from including a statement of the *propositional function* in the narrative presentation of one's theory, which precedes any mathematical operationalizations of it.

The third and last requirement – which is that **the composition of the theory may include what symbolic logic considers to be statement variables and individual variables, but not statement constants and individual constants** – has been implicit in the first two requirements. It directly follows from the explanans-explanandum model's being defined as taking the form of a valid deductive model, which involves a major premise, a minor premise, and conclusion. In symbolic logic, the major premise in a valid deductive argument is a general statement, which may contain only variables and no constants. Thus a theory itself also needs to contain only variables and no constants, whether it is directly inserted into the major premise (which is the case where the theory is already in the form of an equation, as in the natural-science example in Table 1) or it is first operationalized into a mathematical form which is then inserted into the major premise (which is the case in the behavioral-research example in Table 2). This last requirement also suggests another way by which to differentiate explanation from understanding [8], where the latter, as in hermeneutic interpretation, seeks out subjective meanings (meanings enacted and held by the human subjects observed in a particular setting), rather than variables that hold across different settings.

We have identified, above, only three requirements for a theory to satisfy in order to qualify as rigorous according to the positivist explanans-explanandum model of explanation. However, this does not preclude one from identifying additional requirements that the positivist explanans-explanandum model of explanation or any other aspect of positivism imposes on a theory which one wishes to be considered as living up to the standards of positivistly defined rigor.

6. Discussion and Conclusion

In its everyday or lay usage, "explanation" can simply mean "a statement or account that makes something clear" or "a reason or justification given for an action or belief." However, as used in positivist science, "explanation" connotes a certain, specific way of making a valid deductive argument, which in turn has several ramifications for theory and the role it plays in a rigorous explanation.

The first ramification is that statistical analysis not only does not drive theory, but also is not even necessary to be used in the first place – a ramification for which the natural-science example in Table 1 served as the proof of concept. This ramification is especially telling in light of positivism's regard of natural science as the archetype for social science. The statistical analysis of a theory can be rigorous, but this means that rigor is in the statistical analysis, not necessarily the theory or an explanation which uses the theory. Certainly there are occasions when statistical methods are indispensable and therefore invaluable; however, even on those occasions, what makes a theory good and an explanation rigorous goes beyond the statistics. When a positivist perspective is taken, a requirement for a theory to satisfy is that it be able to fit the explanans-explanandum model of explanation, whether or not any statistical reasoning is used.

The second ramification follows from the problem we identified earlier as "operational underdetermination," which refers to the explanans-explanandum model's revelation that a given mathematical operationalization of a theory is just that – namely, just one possible operationalization of the theory. Consider a positivist behavioral-research study that states its theory in the form of prose, operationalizes the theory in the form of mathematical equations, and then uses statistical methods to fit the equations to sample data. The ramification here is that the researcher would need to fully disclose that the research findings pertain only to the chosen operationalization. Such a disclosure should include stating the equations and mentioning that other equations could also represent the same theory. (Currently, research studies rarely state the equations. Moreover, the boxes-and-arrows diagram that is now traditionally used for depicting a theory can be consistent with an infinite number of different ways to operationalize a theory in the form of equations, and therefore does not substitute for stating the chosen equations explicitly.) Also in the interests of full disclosure, such research would need to state two related caveats. The first caveat is: In addition to the operationalization chosen in the given study, there could be other, equally plausible operationalizations of the same theory for which the statistical results could be favorable (i.e., statistically significant estimates of the coefficients of the independent variables and favorable r-square values) and other operationalizations where the statistical results could be unfavorable. The second caveat is: Any favorable results in testing predictions derived from the operationalization of a theory can be claimed not only for these predictions, but also potentially for predictions that have yet to be derived from other,

equally plausible operationalizations that can be offered of the same theory. To address the problem of operational underdetermination, the goal in the long run is to be able to formulate a theory more tightly so that there can be fewer mathematical operationalizations of it – and ideally, just one, as in Table 1's example involving natural science, which, again, positivism regards as the archetype for social science. The symbolic-logic term, "propositional function," refers exactly to this formulation; the propositional function needs to be stated explicitly.

The third and last ramification we mention is that the positivist explanans-explanandum model of explanation does not require the use of mathematics or quantitative data. Certainly, mathematics and quantitative data can make research more expeditious to perform, but nothing in the basics of Hempel's deductive-nomological model of explanation, from which we derived our explanans-explanandum model, requires mathematics or quantitative data. As long as there is the precision required by the symbolic-logic concepts mentioned earlier ("individual variable," "individual constant," "statement variable," "statement constant," and "propositional function"), even qualitative research can craft theory that fits the requirements of positivist explanation. Such qualitative research can fall under the heading of positivist case studies [10][14][15].

In conclusion, researchers who consider themselves positivist need to craft their theories in ways required by positivist explanation. Hempel's deductive-nomological/explanans-explanandum model of explanation is but one rigorous model of explanation. If a positivist researcher or a critic were to call for any other model of explanation, then there would be different requirements for crafting theory – but the lesson is that there would still be requirements, albeit different requirements, for the crafting of theory to satisfy.

7. References

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