

our knowledge of the behavior of observable things and their properties which tests, confirms and disconfirms our theories. For both, the court of last epistemological resort is observation. And yet, as we shall see below, how observation tests any part of science, theoretical or not, is no easy thing to understand.

3 Theories and models

Axiomatization is plainly not the way in which scientists actually present their theories. It does not pretend to be, seeking rather a rational reconstruction of the ideal or essential nature of a scientific theory which explains how it fulfils its function. But there are two immediate and related problems the axiomatic model faces. The first is that nowhere in the axiomatic account does the concept of model figure. And yet nothing is more characteristic of theoretical science than its reliance on the role of models. Consider the planetary model of the atom, the billiard-ball model of a gas, Mendelian models of genetic inheritance, the Keynesian macro-economic model. Indeed, the very term "model" has supplanted the word "theory" in many contexts of scientific inquiry. It is pretty clear that often the use of this term suggests the sort of tentativeness that the expression "just a theory" conveys in non-scientific contexts. But in some domains of science there seem to be nothing but models, and either the models constitute the theory or there is no separate thing at all that is properly called a theory. This is a feature of science that the axiomatic approach must explain or explain away.

The second of our two problems for the axiomatic approach is the very idea that a theory is an axiomatized set of sentences in a formalized mathematical language. The claim that a theory is an axiomatic system is in immediate trouble, in part because, as we noted above, there are many different ways to axiomatize the same set of statements. But more than that, an axiomatization is essentially a linguistic thing: it is stated in a particular language, with a particular vocabulary of defined and undefined terms, and a particular syntax or grammar. Now ask yourself, is Euclidean geometry correctly axiomatized in Greek, with its alphabet, or German with its gothic letters, its verbs at the end of sentences and its nouns inflected, or in English? The answer is that Euclidean geometry is indifferently axiomatized in any language in part because it is not a set of sentences in a language but a set of propositions which can be expressed in an indefinite number of different axiomatizations in an equally large number of different languages. To confuse a theory with its axiomatization in a language is like confusing the number 2 – an abstract object – with the concrete inscriptions, like "dos", "II", "zwei", "10_(base 2)" we

employ to name it. Confusing a theory with its axiomatization is like mistaking a proposition (again, an abstract object) for the particular sentence (a concrete object) in a language used to express it. "Es regnet" is no more the proposition that it is raining than "Il pleut", nor is "It's raining" the correct way to express the proposition. All three of these inscriptions express the same proposition about the weather, and the proposition itself is not in any language. Similarly, we may not want to identify a theory with its axiomatization in any particular language, not even in some perfect, mathematically powerful, logically clear language. And if we don't want to do this, the axiomatic account is in some difficulty, to say the least.

What is the alternative? Let's start with models for phenomena that scientists actually develop, for example, the Mendelian model of the gene. A Mendelian gene is any gene which assort independently and segregates from its allele in meiosis. Notice that this statement is true by definition. It is what we mean by "Mendelian gene". Similarly, we may express the model for a Newtonian system: A Newtonian system is any set of bodies that behave in accordance with the following two formulae, $F = Gm_1m_2/d^2$ – the inverse square law of gravitation attraction – and $F = ma$ – the law of free-falling bodies – and with the laws of rectilinear motion and the conservation of momentum. Again, these four features define a Newtonian system. Now, let's consider what arrangement of things in the world satisfies these definitions? Well, by assuming that the planets and the sun are a Newtonian system, we can calculate the positions of all the planets with great accuracy as far into the future and as far into the past as we like. So, the solar system satisfies the definition of a Newtonian system. Similarly, we can calculate eclipses – solar and lunar – by making the same assumption for the sun, the earth and the moon. And of course we can do this for many more sets of things – cannonballs and the earth, inclined planes and balls, pendula. In fact, if we assume that gas molecules satisfy our definition of a Newtonian system, then we can predict their properties too.

Notice that the definition given above for a Newtonian system is not the only definition we could give. Following Richard Feynman, we may, for example, substitute for the inverse square formula one which relates the gravitational potential on an object at a point to the average gravitational potential surrounding that point: $\Phi = \text{average } \Phi - Gm/2a$, where Φ is the gravitational potential at any given point, a is the radius of the surrounding sphere on the surface of which the average potential, average Φ , is calculated, G is the same constant as figures in the formula above and m is the mass of the objects at the point on which gravity is exerted. Feynman argued that one may prefer this formula to the usual one because $F = Gm_1m_2/d^2$ suggests that gravitational force operates over

large distances instantaneously, whereas the less familiar equation gives the values of gravitational force at a point in terms of values at other points which can be as close as one arbitrarily chooses. But either definition will work to characterize a Newtonian gravitational system.

Now the reason we call these definitions models is that they "fit" some natural processes more accurately than others; that they are often deliberate simplifications which neglect causal variables we know exist but are small compared to the ones the model mentions; and that even when we know that things in the world don't really fit them at all, they may still be useful calculating devices, or pedagogically useful ways of introducing a subject. Thus, a Newtonian model of the solar system is a deliberate simplification which ignores friction, small bodies like comets, moons and asteroids, and electric fields, among other things. Indeed, we know that the model's exact applicability is disconfirmed by astronomical data on, for example, Mercury's orbit. And we know that the model's causal variable does not really exist (there is no such thing as Newtonian gravity which acts at a distance; rather space is curved). Nevertheless, it is still a good model for introducing mechanics to the student of physics and for sending satellites to the nearest planets. Moreover, the advance of mechanics from Galileo and Kepler to Newton and Einstein is a matter of the succession of models, each of which is applicable to a wider range of phenomena and/or more accurate in its predictions of the behavior of the phenomena.

A model is true by definition. An ideal gas is by definition just what behaves in accordance with the ideal-gas law. The empirical or factual question about a model is whether it "applies" to anything closely enough to be scientifically useful – to explain and predict its behavior. Thus, it will be a hypothesis that the Newtonian model applies well enough to, or is sufficiently well satisfied by, the solar system. Once we specify "well-enough" or "sufficiently well satisfied", this is a hypothesis that usually turns out to be true. The unqualified claim that the solar system is a Newtonian system is, we know, strictly speaking false. But it is much closer to the truth than any other hypothesis about the solar system except the hypothesis that the solar system satisfies the model propounded by Einstein in the general theory of relativity. And a theory? A theory is a set of hypotheses claiming that particular sets of things in the world are satisfied to varying degrees by a set of models which reflect some similarity or unity. This will usually be a set of successively more complex models. For example, the kinetic theory of gases is a set of models that begins with ideal-gas law we have seen before, $PV = rT$. This model treats molecules as billiard balls without intermolecular forces and assumes they are mathematical points. The theory includes a subsequent improvement due to van der Waals, $(P + a/V^2)(V - b) = rT$, in which a

represents the intermolecular forces and b reflects the volume molecules take up, both neglected by the ideal-gas law. And there are other models as well, Clausius's model, and ones that also introduce quantum considerations.

Exponents of this approach to theories, according to which they are sets of models, that is of formal definitions, along with claims about what things in the world falsify these definitions, call their analysis the "semantic" account of scientific theories and contrast it to the axiomatic account which they call the "syntactic" account for two related reasons: (a) it requires derivation of empirical generalizations from axioms in accordance with rules of logic, which are the syntax of the language in which the theory is stated; (b) the derivations which logical rules permit operate on the purely formal features – the syntax – of the axioms, and not the meaning of their terms. Notice that although models will be linguistic items on the semantic view – definitions – hypotheses and theories will not be linguistic items but (abstract) propositions expressible in any language, to the effect that the world or some part of it satisfies to some degree or other one or more models, expressed indifferently in any language convenient for doing so.

But surely this is not the chief advantage of the semantic view, by comparison to the syntactic view. For after all, the axiomatic account may well be best understood as the claim that a theory is a set of axiom systems in any language that expresses all the same propositions as axioms or theorems, or that it is the set of all such axiom systems that best balance simplicity and economy of expression with power in reporting these propositions. If the linguistic or non-linguistic character of theories is a problem, it is a rather technical one for philosophers, which should have little impact on our understanding of scientific theories. The advantage of semantical over syntactical approaches to theories must lie elsewhere.

One advantage the semantical approach has of course is that it focuses attention on the role and importance of models in science in a way that the axiomatic account does not. In particular, it is hard for the axiomatic analysis to accommodate the formulation of models known from the outset to be at most false but useful idealizations. It won't do to simply to interpret $PV = rT$ not as a definition of an ideal gas, but as an empirical generalization about real objects to be derived from axioms of the kinetic theory of gases, if we know that the statement is false and could not be true. We don't want to be able to derive such falsehoods directly from our axiomatic system. For such derivations imply that one or more of the axioms is false. What we may want is to find a place for models within an axiomatic approach.

A related advantage of the semantic approach is often claimed for it. In