THE ROLE OF MODELS IN SCIENCE

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The intention and the result of a scientific inquiry is to obtain an understanding and a control of some part of the universe. This statement implies a dualistic attitude on the part of scientists. Indeed, science does and should proceed from this dualistic basis. But even though the scientist behaves dualistically, his dualism is operational and does not necessarily imply strict dualistic metaphysics.

No substantial part of the universe is so simple that it can be grasped and controlled without abstraction. Abstraction consists in replacing the part of the universe under consideration by a model of similar but simpler structure. Models, formal or intellectual on the one hand, or material on the other, are thus a central necessity of scientific procedure. The purpose of this paper is to analyze the usefulness and the limitations of the diverse forms of scientific models.

An investigator is often not aware of his methodological procedure, nor is it indispensable that he should have this awareness. Important scientific contributions, especially of an experimental character, can be made even though the experimenter does not realize that all good experiments are good abstractions.

An experiment is a question. A precise answer is seldom obtained if the question is not precise; indeed, foolish answers—i.e., inconsistent, discrepant or irrelevant experimental results—are usually indicative of a foolish question.

Not all scientific questions are directly amenable to experiment. There is a hierarchy of questions whose levels are determined by the generality of the answers sought. Thus the question of what a certain drug, e.g., cebadine, does to a certain manifestation of a nerve impulse, e.g., the spike potential, belongs to a relatively "low" level in the hierarchy of physiological questions, because it deals with a narrowly restricted phenomenon. An experimenter might formulate and answer that question precisely, and yet have only a vague, intuitive appreciation of its "higher", more general and abstract implications, such as the action of all drugs belonging to a certain chemical group on the spike potential, or the relations between spike potential amplitude and other manifestations of nerve activity.

As a rule "high" order, very abstract and general questions, are not directly amenable to an experimental test. They have to be broken down into more specific terms, terms directly translatable into experimental procedure. There are thus two qualitatively different operations involved in the process of formulating the test of a general statement, or in the converse process of building a theory from experimental data. One of these operations consists in moving up or down the scale of abstraction; the other requires the translation of abstraction into experiment, or vice versa. The good experimenter has unusual ability in the second procedure; he is capable of freely interchanging symbols and events. The theorist, on the other hand, deals mainly with the first type of operations, those at various levels within the realm of abstraction.

It might appear that the most expedient method of approaching a problem scientifically would be to formulate the most general question or questions possible, and then to subdivide these questions into less abstract statements, until first order abstractions, directly testable, would be reached. This method is applicable only exceptionally, because very abstract questions can only be framed after data have been collected, and the immediate implications of these data have been grasped. Problems are therefore usually approached in the opposite direction, from the factual to the abstract. An intuitive flair for what will turn out to be the important general question gives a basis for selecting some of the significant among the indefinite number of trivial experiments which could be carried out at that stage. Quite vague and tacit generalizations thus influence the selection of data at the start. The data then lead to more precise generalizations, which in turn suggest further experiments and progress is made by successive excursions from data to abstractions and vice versa.

After these general considerations we may proceed to the analysis of the several scientific models. A distinction has already been made between material and formal or intellectual models. A material model is the representation of a complex system by a system which is assumed simpler and which is also assumed to have some properties similar to those selected for study in the original complex system. A formal model is a symbolic assertion in logical terms of an idealized relatively simple situation sharing the structural properties of the original factual system.

Material models are useful in the following cases. *a*) They may assist the scientist in replacing a phenomenon in an unfamiliar field by one in a field in which he is more at home. They thus may have important didactic advantages. The history of the development of engineering illustrates this mode of usefulness. During the 18th and 19th centuries the success of Newtonian dynamics so dominated physics that electrical problems were often approached via mechanical models. After the work of Faraday and Maxwell, and with the growth of the large scale electrical industries, the development of electrical knowledge outstripped signally that of mechanics. Throughout this century, electrical models have been used to solve mechanical problems.

b) A material model may enable the carrying out of experiments under more favorable conditions than would be available in the original system. This translation presumes that there are reasonable grounds for supposing a similarity between the two situations; it thus presupposes the possession of an adequate formal model, with a structure similar to that of the two material systems. The formal model need not be thoroughly comprehended; the material model then serves to supplement the formal one.

Sometimes the relation between the material model and the original system may be no more than a change of scale, in space or time. As an example of a change of a spatial scale, at any proving ground, experiments on shells will not be carried out with large, expensive and unwieldy calibers, but with handy, cheaper, small calibers. Another example is the use of small animals, instead of large ones, for biological experiments: certainly any physiologist will work as much as possible on a dolphin rather than on a sulphur-bottom whale.

As an example of a transformation of the time scale may be mentioned the employment of drosophila in the study of genetics and population problems, in view of its rapid rate of multiplication.

A further instance of a transformation which facilitates experimental procedure is the use of transparent plastic models with adequate elastic properties for the study of the strains in steel structures. The transparency allows the use of polarized light to make the internal stresses directly observable.

While material models may thus render important services it may be emphasized that not all material models are useful. It is likely that the criteria *a* and *b* discussed above are not only sufficient but also necessary conditions for a useful material model. If the formal model which suggests a material one is weak and trivial, the latter will be irrelevant and barren—i.e., a gross analogy is not scientifically fruitful. Again, if a material model does not suggest any experiments whose results could not have been easily anticipated on the basis of the formal model alone, then that material model is superfluous. Finally, if a model has a more elaborate structure and is less readily amenable to experiment than the original system, then it does not represent a progress.

To exemplify, the long series of ether models in terms of elastic solids and gyroscopes which were the fashion among physicists during the eighties and nineties of the 19th century, have proved to be sterile and actually misleading, since they diverted the attention of scientists from the essential features of the problem involved. As Faraday and Herz had already seen, the important need in electrical knowledge was a sound field theory free from the operationally meaningless props of elaborate material analogies. As another example of an apparently useless analogy, the nitric acid-iron wire model of Lillie for nerve fibers may be mentioned. Although featured very prominently in most textbooks on the subject, iron wire dipped in nitric acid is not easier to experiment with than nerve fibers and there is no particular mathematical difficulty in the formulation of the problems involved. The phenomena of passive metals are not better understood than those of nerve, and involve quite as much physical conjecture; from this standpoint, were it not that the analogy is probably only gross, the useful model in the pair would be the nerve axon instead of the wire.

As an introduction to the analysis of theoretical models it is appropriate to define what will be meant by a "closed box", as opposed to an "open box" problem. There are certain problems in science in which a fixed finite number of input variables determines a fixed finite number of output variables. In these, the problem is determinate when the relations between these finite sets of variables are known. It is possible to obtain the same output for the same input with different physical structures. If several alternative structures of this sort were inclosed in boxes whose only approach would be through the input and output terminals, it would be impossible to distinguish between these alternatives without resorting to new inputs, or outputs, or both. For instance, a given electrical impedance as a function of frequency can be realized with many different combinations of resistances, capacitances and inductances. As long as closed boxes containing such elements are only tested for self and mutual impedances across the terminals, their accurate internal structure cannot be determined. To determine that structure additional terminals would have to be used. The more terminals available, the more open the system. An entirely open system would need an indefinite number of terminals.

It is obvious, therefore, that the difference between open-box and closed-box problems, although significant, is one of degree rather than of kind. All scientific problems begin as closed-box problems, i.e., only a few of the significant variables are recognized. Scientific progress consists in a progressive opening of those boxes. The successive addition of terminals or variables, leads to gradually more elaborate theoretical models: hence to a hierarchy in these models, from relatively simple, highly abstract ones, to more complex, more concrete theoretical structures.

The setting up of a simple model for a closed-box assumes that a number of variables are only loosely coupled with the rest of those belonging to the system. The success of the initial experiments depends on the validity of that assumption. As the successive models become progressively more sophisticated the number of closed regions may actually and does usually increase, because the process may be compared with the subdivision of an original single box into several smaller shut compartments. Many of these small compartments may be deliberately left closed, because they are considered only functionally, but not structurally important.

At an intermediate stage in the course of a scientific inquiry the formal model may thus be a heterogeneous assembly of elements, some treated in detail, that is specifically or structurally, and some treated merely with respect to their overall performance, that is, generically or functionally. Thus, in the study of the nervous system, for many purposes synapses may be considered merely as regions where impulses are delayed, disregarding any question as to the method by which this delay takes place, and disregarding also other properties of synapses such as the fact that they are regions where facilitation or inhibition can occur.

A beautiful example of the progressive concretization of a theoretical model by the successive introduction of additional variables is furnished by the historical development of the theory of sound. It began mathematically as a system of linear partial differential equations in a homogeneous continuous medium. This simple model was, and still is useful for the representation and prediction of the transmission of sound of moderate intensity. For intense sound this theory failed. It was replaced by non-linear differential equations based on hydrodynamics and thermodynamics. In the study of shock waves it was realized that the dimensions of the regions of shock are those of the mean free path of a particle in a gas. Any theory which is to be satisfactory in this domain should take into account the molecular nature of the gas. As a first approximation the gas may be taken as perfect: that is it may be supposed to consist of particles without forces between them. The next, and more accurate theory, not yet developed, will take account of the forces between the particles; a still more mature theory will represent these forces in the space of quantum mechanics and not in that of the Newtonian theory.

So far this discussion has dealt mainly with the elaboration of theoretical models in order to explain observed facts—in other words, with the scientific search for abstract models with a structure equivalent to that of a given experience. Science is also concerned with the reverse process, namely, that of embodying an abstract structure into a concrete entity of similar structure, usually an apparatus or machine with a definite purpose. The traditional approach to such designs is empirical and largely accidental, but the scientific approach is possible and has already shown its validity. In this method the apparatus is first designed from the closed-box point of view, which should be obtained, when possible, by a theoretical minimization process, which is often statistical. For instance, if a wave filter is desired to separate telephone messages from noise, the first step is to determine the statistical composition of the messages and noises carried by the line. Given this composition there is a characteristic of the filter which best separates message and noise—i.e., a characteristic which minimizes the effects of the noise on the messages. For any characteristic there will be many ways of constructing an appropriate filter. The requirements are of an open-box nature, but the elements used in the construction may be treated on a closed-box basis. Other considerations, not necessarily relevant to the problem as stated, will determine the choice.

We have shown that scientific knowledge consists of a sequence of abstract models, preferably formal, occasionally material in nature. We shall now proceed to examine the results of carrying model-making to the limit. Consider first material models. They start by being rough approximations, surrogates for the real facts studied. Let the model approach asymptotically the complexity of the original situation. It will tend to become identical with that original system. As a limit it will become that system itself. That is, in a specific example, the best material model for a cat is another, or preferably the same cat. In other words, should a material model thoroughly realize its purpose, the original situation could be grasped in its entirety and a model would be unnecessary. Lewis Carroll fully expressed this notion in an episode in *Sylvie and Bruno,* when he showed that the only completely satisfactory map to scale of a given country was that country itself.

The situation is the same with the theoretical models. The ideal formal model would be one which would cover the entire universe, which would agree with it in complexity, and which would have a one to one correspondence with it. Any one capable of elaborating and comprehending such a model in its entirety, would find the model unnecessary, because he could then grasp the universe directly as a whole. He would possess the third category of knowledge described by Spinoza.

This ideal theoretical model cannot probably be achieved. Partial models, imperfect as they may be, are the only means developed by science for understanding the universe. This statement does not imply an attitude of defeatism but the recognition that the main tool of science is the human mind and that the human mind is finite.

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