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MODELS IN SCIENCE

Model children—the painter and his model—a model of a foundry—a miniature model of an aeroplane—Bohr-Rutherford's model of the atom. If one seeks the common element of these various objects and concepts, it would appear to be a comparison between two things displaying some common characteristics, one of which, at least, is the result of a creative effort on the part of man. One of these objects is called a model. But it can be the man-made one or the other which will be, for example, a given thing, either natural or artificial. A similar ambiguity exists in French with the word *hôte*; it is the notion of hospitality which prevails rather than the identification of one of the parties. In the case in question the relation is that of a form or structure which in both parties corresponds in some aspects, if not in all, to the supplementary criterion of human and voluntary origin of one of them. It also often happens that the thing called model in the relationship is single, whereas the other is multiple and varied both in its homologous characteristics and the additional ones it may possess. In the particular case of models used in science, the models themselves are a result of the creative effort of man. The second

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party of the relationship is an object in nature: an atom, the planetary atmosphere, the organ of a live being. We have a reverse situation in the case of a work of art and its model, an object taken from a world exterior to the artist. In both cases the characteristics representing the similarities which deermine the relationship are generally far from exhausting the resources of either the object or the natural model and of the work of art or the man-made model. We shall see, in fact, that scientific models are an approximation or rather a simplification of the natural objects studied, but that when their logical construction is carried further they can become endowed with new characteristics whose closeness to the natural object reveals in the latter some features which until then had been ignored, neglected or misunderstood. As for works of art it is a platitude to say that they are both richer and more concise than the original models if there are any and that, on closer examination of the latter, features will be found which until then had been unseen.

We shall now endeavour to bring to light another aspect of model relationship in science and in art which is both common and inverted. That is its compulsory character, for this relationship is in fact one of the fundamental mechanisms of thinking. Every scientist thinks continuously in terms of models—even if he does not admit it to others or to himself. Equally there is no work of art without a model, be it exclusively interior and sometimes even unsuspected by the artist himself. Here are two examples: Flaubert stating "*Madame Bovary c'est moi*"—Lord Kelvin admitting that when evolving the theory of gases he saw little red balls in movement. We must now ascertain the exact part played by models in science, or rather the part played by the various types of model, for even if we restrict our study to the field of science we shall be faced with a fairly large variety. Perhaps the best thing would be to try to define the boundaries of the notion of the model in science: thus, what distinction should be established between a model and a theory or a model and a diagram, between a model and an instrument of analogy or a model and an instrument of demonstration, finally between a model and an artificial organ—heart or kidney? We can thus, in dealing with concrete cases, circumscribe if not solve the problem for, as Samuel Butler put it—to define is to surround with a wall of words a jungle of ideas.

With regard to the first boundary it might be well to look for the degree of abstraction of a model, that is the point beyond which it becomes a theory. Here we are immediately confronted by the question of quantity: what fraction of the characteristics of the object of the phenomenon under study should the model possess? what fraction of the combined characteristics of the model not belonging to the object can be tolerated? In other words, when one considers the two combinations of characteristics, those of the model and those of the object under study, what relative importance should be given to the intersection of these combinations? What happens in the case of a theory?

Let us take as an example the kinetic theory of gases. One does not refer to a "kinetic model," yet I am sure that the great majority of physicists, like Lord Kelvin, tend to materialise their reasoning when studying the theory, through a vision of billiard balls in motion, fictitious balls, doted with impracticable properties because of their infinitely smooth surface and elasticity and defined only by their mass and the co-ordinates and movement of their centres. I think that one does not refer to a model in this case because too many of the concrete characteristics of the billiard ball as a mechanical model have been eliminated and one is left with scarcely more than equations, that is to say an abstract theory. A theory which is too abstract moreover, since it has become necessary to re-invest molecules with certain concrete properties, such as rotations or internal vibrations, which means that they must be imperfectly spherical and smooth and that they must possess a given structure and defined dimensions. The model then comes to the fore and one speaks of molecular models of compound bodies. These models become diagrams when it is a case of explaining internal links such as valences: thus in organic chemistry substances are represented "diagramatically" by all these links and in these diagrams the atoms are placed at the junctions and have as properties scarcely more than the arithmetical multiplicity of the links which terminate at these junctions.

The example of Kekule's hexagonal model for benzene—the benzenic ring—is fundamental for the entire chemical range of aromatic compounds.

Another boundary exists between model and apparatus, be it an instrument of demonstration or of research. Let us take an example in hydraulics. Models are built of rivers, particularly of estuaries, care being taken to reproduce different characteristics of the natural object under study—not all, but to our mind the more important. These models are intended for research, for in function their operational behaviour brings to light effects which it would be extremely difficult to calculate. They are also instruments of demonstration. The same applies to reduced models of ships or aircraft when they are submitted to the movement of water or of air in trial tanks or wind tunnels. The training of pilots by the use of reduced models makes the latter instruments of demonstration.

What new quality does the model thus acquire? It possesses of course characteristics similar to those of the object under study, as in the case of the kinetic theory of gases, but the laws which govern the relationships of these parameters between themselves and with the variations of time and space—even though their principles are well known—lead to calculations which are too complex for regular use. Advantage can, then, be taken of the fact that the man-model, being easier to handle than the studied object, will, thanks to its functioning and the variety of operations that it can carry out, achieve numerical results which can be applied to the object. Many precautions must of course be taken for the result to be satisfactory: the choice of parameters employed which should be quite indepedent of the others, dissimilar characteristics of the object and the model, verification of the applicability of the same laws to both objects, etc. But we known how many services this method of using operational models can render.

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Due to the constant development of science the models which are employed also move from one of the various categories which we have examined to another. Thus some diagrammatic models have become more and more abstract and theoretical, whereas others have become more and more concrete and descriptive: Bohr's atom, that is to say a planetary-type system of electrons around a nucleus, has changed, because of undulatory mechanics, into a continuous distribution of probabilities of these electrons' presence around the nucleus so that in modern treatises graduated colours replace the former circular or elliptical trajectories in the diagrammatical representation of atoms. By becoming closer to reality the model has become less concrete. On the contrary the diagrams called "developed formulae" used in organic chemistry in the nineteenth century have become concrete models since measurements have been taken of the distances separating the atoms and of the angles created by the valences which link the atoms together. In other cases models in the form of demonstration instruments have given birth to actual machines. Thus the model of the magnetic earth (Terella) on which Störmer used to direct cathodic rays in order to demonstrate the movements of electrons as the cause of the aurora borealis, has inspired the construction of powerful instruments which aim at enclosing the swift electric particles in magnetic jars, as is effectively the case in circumterrestrial space, and whose object is in reality the construction of machines containing very hot plasma in which the reaction of the fusion of hydrogen nuclei could be realized.

To the various types of models correspond various functions: explanation, demonstration, operation, discoveries. And to the movement of the models from one category to another corresponds a change of their functions. A model which has been thought out to fix ideas, to provide a resting-stage to scientific thought, which has therefore an explanatory or demonstrative function, can prove to be the origin of new discoveries. Supplementary to those characteristics which are the support of analogy, of isomorphism, which gave the models their qualities of models, there can be some characteristics which intimate a new category of isomorphism and thus lead to the discovery of unsuspected relations. We have a good example of this in the theory of electromagnetism. Maxwell endeavoured to find an interpretation of the remote action of electric charges—an action reminiscent of gravitation—and at the same time the link beween this action and magnetism. Faraday had attempted to construct a mechanical model in which the lines of force became physical entities connecting the charges and forming a vehicle for these forces, and Maxwell, as a true physicist, refused to acknowledge remote actions through a physical void, and evolved an accurate mechanical model of Faraday's entities. This model was made of tubes which contained an incompressible fluid, the velocity of which represented electric force and provided an interpretation for a good many aspects of observations on electrostatics and electric induction. Maxwell then improved it in order to allow for the play of magnetism, but then the cylinders representing the tubes of magnetic force had to revolve around their own axis and at the same time carry the force along this axis. Cylinders with parallel axes revolving in the same direction and touching one another would be submitted to tremendous friction: Maxwell therefore separated them by true ball-bearings. Apart from their rotary movement these balls did not move as long as the cylinders rotated at the same speed, but they started moving as soon as a variation in speed occurred in any part of this forest of revolving cylinders. If one admitted that these balls were the bearers of electric charges then the mechanical model of electromagnetic induction appeared as if by a mental conjuring trick! Maxwell did not stop at that; it is well known that he went on improving his mechanical model until he was finally able to reproduce electromagnetic vibrations. Identification by light waves, by proving that the velocity of the two types of wave was identical, soon followed. Maxwell then set down the equations of those waves, and was then able to dispose of the mechanical model just as one does away with a scaffolding, as Whittaker would say. In this instance one can follow along parallel lines the development of the discovery and the construction of the model; the latter gives a concrete expression to knowledge and precedes it, in that it shows the alternate requirements of both, until the mathematical representations based on the model are firm enough to dispose of it. Of course, although tremendous progress had been achieved, the sudden disappearance of the model, leaving in its place laws and equations which were perfectly adequate but had no material support, led back to the problem that Maxwell had tried to solve: what was the vehicle of these actions which had been shown to be more complex than simple remote attraction of gravitation? Ether, whose existence Maxwell could but postulate, then set a fundamental mechanical problem, for its properties were so strange that it could not be likened to any known physical medium, not even by means of extrapolation. It has been said that the disappearance of the mechanical model, leaving only equations, is like the disappearance of the Cheshire Cat, of which nothing remained except its smile. We know that the research for the properties of ether and the pursuit of a new mechanical model acceptable to the mind have led to the experiments of Fizeau and later of Michelson and Morley, and that the failure of these mechanistic attempts have led Einstein to the theory of realitivity.

Against this example of the stimulating power of a model in a discovery one must not omit to quote examples of inhibiting powers of models if they are taken too seriously, if one puts too much faith in them—a word which the true scientist must eliminate from his vocabulary. The geometrical models of crystals in which complex cells showing all the symmetrical characteristics of crystal formed the fundamental network, impeded for a long time recognition, in the elements of this network, of the atoms themselves, and it was not until X-rays were used that this fortress in the theory of matter could be overcome. Even Bohr-Rutherford's model of the atom, model in the shape of a miniature solar system, gave rise to fallacious interpretations of numerous properties of matter. Since the model was taken literally it was assumed that the electronic orbits of the neighbouring atoms could be attributed linking and contacting functions, which had to be abandoned after the advent of undulatory mechanics. One can even say that in this field of fundamental physics the models have given way to pure mathematics, that is they have become more and more abstract until they are divested of all the characteristics which related them to classical mechanics. They have therefore lost their relaxing quality, if one may use that word, for all those who are not absolutely at ease with pure mathematical symbolism: those who are not sufficiently pure Pythagoreans.

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We have up till now limited our study to the field of physics. The reason for this is that the advanced stage reached in the theoretical and experimental foundations of this field of science allowed us to unfold the whole range of significances and functions of models. But we shall find some similar cases in biology or in the heterogenous complex currently called sciences of the earth. And we shall see that there too the model has great importance, whether it be mechanical, geometrical or graphical. Thus, on entering a modern bio-chemical laboratory one is confronted by a whole range of elegant, spiral-shaped constructions formed of spheres linked together and somewhat warped by their proximity. These are the ADN and ARN chains. Others, vermicelli-like and much less elegant, are protein models. The object of these constructions is to represent as faithfully as possible the spatial relationships of atoms, as well as the chemical functions formed by their assemblage, in the macromolecules of protoplasm and they have already made it possible to group very synthetically numerous chemical and biological properties of these extremely complex substances. Let us take the precise example of a model which has dominated—and still dominates—the whole field of immunology and which is commonly used in several other branches of cellular physiology—that is the model of the "lock and key." It is based on the idea that certain complex chemical groups belonging to one of the giant molecules of bio-chemistry—either proteins, ADN or ARN, etc.—can be applied strictly preferentially to groups which are complementary to other macromolecules, just as in the case of a key when it is inserted into the corresponding lock. The result of this application is the annulment or considerable alteration of the capacity of chemical action which these groups had when they were free. Although not quite so marked, this modification can extend to all the other parts of the macromolecules considered. In other words it creates a new, more or less durable biochemical complex. This principle extends to the concrete models of the duplication of chromosomes during mitosis and of their junction during meiosis; to the models of the synthesis of proteins through the "informative" action of ARN; to certain theories on the permeability of cellular membranes and on the functioning of the nervous synapsis. It is also thanks to such models that the bacteriostatic action of certain antibiotics can be interpreted. There is, of course, an abstraction behind the somewhat primitive model of the lock and key, that is the information provided by the pattern of the key and by the specific groups of the atoms in the molecules. When this principle is applied to a particular phenomenon such as the duplication of chromosomes or the synthesis of proteins in ribosomes, the model is complicated by additional mechanisms such as, for instance, the "lightning fastener" device which in all likelihood comes into play when a series of specific groups—a coded series—is reproduced element after element, starting from one end of the chain. These diagrams are very useful for guiding biologists in the multitude of possible experiments and for indicating those which will prove the most significant. Even though they are only models and not rigorous representations, it is very probable that when the latter are established they will retain very many features of the initial models. In other words, the evolution observed in this case is progressively more concrete, as in the case of developed formulae in organic chemistry, that is to say it is the contrary of what we observed in quantic physics.

As we had foreseen, concretisation can be carried even further when a model is transformed into an instrument which can have a function either for teaching or for useful operations. Let us take a biological example: that of the heart. For a long time already physiologists have used physics in order to obtain mechanical and electrical models of the heart: it has been possible to imitate faithfully its complex pumping system with materials which are in harmony with the components of blood. The autonomous nervous system has also been imitated by appropriate electric circuits, in particular the so-called "relaxation" devices which produce a precise rhythm which can be regulated. These models of the heart, which are interesting both for demonstration and for research purposes, have been carried further; they have led to the creation of actual artificial hearts with a pumping system in the case of temporary substitution for the natural organ, or with an electric system only in the case of instruments used permanently to correct a deficiency of this nature in the natural organ.

This technique of imitation by models is not limited to sound hearts. In fact a very interesting attempt has been made to evolve a model of the fibrillation of the heart muscle, a very important pathological phenomenon, by using elements of the electronic circuits employed in computers, or "electronic brains." In this way it was made possible to imitate the self-regulation of this fibrillation and to draw conclusions as to the number of elements necessary, to their interconnections, and characteristics. One can forecast an interesting future for this technique of models of illnesses. Actually physiology can easily provide us with numerous other examples: for instance models of the retina, models of the nervous synapsis, models of kidneys or lungs. Although their isomorphism with the genuine organs is of course always only partial, all these models render great services to research and—when they are given a concrete form—to medicine.

Let us see now what happens in a scientific field placed perhaps by its structure between the two cases which we have examined, that of sciences relating to the earth. Geophysicists have long ago established models of the globe, based chiefly on the results of seismology. These models have recently been made more complicated and concrete when it became necessary to explain terrestrial magnetism and its modifications in time. They also explain the very particular shapes of the continents, and especially for the eastern and western Atlantic coasts. Isostasis, the drift of the continents and the convectional movements found in the layer sub-jacent to the earth's crust, have led to the complications and improvement of the model with spherical concentric layers: a central germ, a nucleus, a middle layer and a superficial crust. Similarly, the old model of the atmosphere governed solely by the law of gravitation has become complicated when precise measurements of heat, turbulence, composition and ionisation were taken. In these evolutions, as also in those which have occurred in models of stars, and especially those of the sun, one can observe at the same time the two tendencies noted in quantic physics and biology: on the one hand the models become more and more mathematical on the other more and more concrete and precise.

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In any case the use of models as the support of theoretical thought and as a source of inspiration for research has and will always prove to be very important, if not indispensable. However, I would like to make a remark which does not only apply to them but also in a certain sense to techniques and to theories. It concerns a problem of operational research regarding the evolution undergone by these three aspects of science, corresponding to the progress of knowledge of the objects and phenomena of which they give an intelligible representation, or which can be attained through them. This evolution of the models and of the theories or techniques cannot always be continuous or take place by slight successive changes: from time to time there must intervene an important mutation, by the application of new principles. What are the conditions in which one should decide to practise this "total revision?" If the decision is too hasty, the new model, the new theory, or the new apparatus can prove much less useful than the old ones if properly renovated. If it is too late, that is to say if one keeps to traditional formulas, once they have become excessively complicated, one runs the risk of seeing research become fruitless and researchers discouraged.

This is what happened to the old geocentric model of the planetary and solar system. The orbits had to be circular, for what appeared an obvious reason and the systems followed one another, becoming more and more complicated by cycloids until the tardy decision was finally taken to put the sun in the centre and to make museum-pieces of cycloids, with which were later classified the four elements, phlogiston, heat and ether, all residual products of mutations of the same sort. The first signs which forewarn scientific circles that such a transformation will become necessary are often the excessive complications which have to be imposed on traditional models. Thus, the extraordinary properties attributed to "ether," the supposed carrier of light waves, made its existence more and more problematic, until the theory of relativity suppressed it altogether. It is then up to research planners, to theoreticians, to experimenters, to choose the right moment for breaking with old habits of thought and action.

May I be allowed, in this connection, to draw a parallel between scientific models and myths. Are the latter not also models, whose purpose is to make intelligible great natural phenomena or biological and social facts? Models constituted from known elements, immediately accepted and understood, like our mechanical models, home-made—as Claude Lévi-Strauss would say—from familiar notions so as to form complexes which are isomorphous with those complexes which have to be explained and integrated with thought. Myths also develop either towards theory and abstraction or towards materialisation and particularization, according to requirements. They too are sometimes subjected to stringent revisions or else are of a sudden replaced by newcomers. Scientists are at times acutely conscious of the processes we have described and of the dangers which certain models present when they tend to become myths. They then have to sound the alarm and remind their colleagues, less conscious of the danger, of the inhibiting factor of Aristotle's doctrines, even though—according to Galileo, this philosopher would not have hesitated to alter his opinions and himself correct his books had he known the new astronomic discoveries.

But let us follow the myth further, in its most abstract aspects, where its symbolism is reduced to relations almost entirely stripped of any representation, relations to which only mathematics can give a logically constructed frame. It seems to me that it is then no longer isolated, in the place it occupies in the arsenal of ideas. Very close to it I see the "archetypes" on which Kepler based his cosmology—and even, alas, his astrology. One of these archetypes linked a trinitarian "myth" with the elements of the circle: centre, circumference and intermediate surface. Was not the one based on the sphere—the finest of volumes—also a "model", from which Kepler deduced the law of photometry, that is to say a decrease of light inversely to the square of the distance from the source? With this model Kepler had come close to Newton's law, for he was acquainted with Galileo's mechanics and had himself established the laws of the movement of planets around the sun. The prevention of discovery was perhaps solely the myth which endowed celestial bodies with a soul: the latter could scarcely, in these conditions, be expected to abide by laws which governed the fall of a stone—or of an apple! It was essential, therefore, to first deprive the planets of their sacred character.

Fruitful models, inhibitory myths, here come very close to profoundly satisfying symbolisms. But let us return to present-day science. High energy physicists are now putting forward highly symmetrical abstract structures under the name of US2, US8, US12, (US stands for unitary symmetry) which make it possible to classify, place and sometimes foresee the properties of the so-called "elementary" or "fundamental" particles, those which appear as ultimate elements of matter and energy in nuclear collisions. These structures should, I think, be considered as models, which it is to be hoped will prove fruitful. It may, however, be necessary, in order to make full use of them, to desecrate both the past and the future and to remove the head and the feathers from the arrow of time.