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# Introduction. Modelling is the key to science

*Abstract:*

*In this introductory chapter I want to draw attention to the importance of modelling activity in scientific work. Models are not just a very valuable aid to research. They are actually able to represent the structure of things. In this way, modelling is the essential procedural step in doing science. Those who emphasized observation, experimental controls, and the close relations that exist between science and technology were not wrong, but these emphases have long obscured the real aim of science: to proceed from phenomena upward to their principles, that is, to the structures which govern and explain phenomena.*

*To begin, I will recall that models represent the structure of systems; the system can be real or imaginary. Then I will show that science seeks to model three different kinds of structures when it studies an empirical system. The result is that scientific models have different roles, depending on whether they are intended to represent imaginary systems, or one of the three structures of an empirical system. I conclude with a defence of the fruitfulness of artificial models.*

*Keywords:*
system, isomorphic, realism, mechanism, properties, empirical models, formal models, artificial models

## 1 Models represent systems

There are different kinds of scientific models: mathematical models, conceptual models, statistical models, geometrical figures, diagrams, geographical maps, computer modelling, neuronal models, etc. The great number of things which get called models creates some confusion, and we may get the feeling that a 'model' is just another name for a catch-all. In reality, though, all the types of representations that we call models have something in common: they represent systems. A system is a set formed from subsets, relations between these subsets, and relations between the subsets and the set they belong to. A system may be linked to an environment, may indeed be a subset of an environment. Two components are thus enough to make a model: representations of relations, and representations of sets or subsets.

The network of relations between subsets in a system and the network of relations between subsets in another system are not the same. The network that belongs to a particular system is called the structure of that system. The structure of the system is that which the model seeks to represent. The structure of a system is more than often complex, and the model only represents then part of it, perhaps only a very small part.

## 2 The fictive character of scientific models

It is common to emphasize the fictive nature of scientific models. Many proposed models represent imaginary systems. These can play an exploratory role, provide heuristic support, enable us to test hypotheses, or illustrate arguments for didactic purposes. Models can also aid in the conception of technical arrangements that allow us to act on phenomena. But even when a model purports to represent a real system, it appears to be something fictive in nature. For the model offers us a very incomplete representation of the given system, one in which only the structure of the given system is represented (and usually only a small part of that). Moreover, there is often not even any perceptible resemblance between the model and the part of the system that is supposed to be represented. All this leads us to think that models can never be anything but mental constructions, that modelling is not intended to reflect reality, and that models are good insofar they are useful. This point of view is widely shared today. In my opinion, it's better to give it up.

## 3 The realism of models

The ability mathematical representations have, to teach us about reality, is amazing. How is it that the representation of reality can be accomplished without any dependence on perceptible resemblance to the things? This is not only true for mathematics, but also for ordinary language and in fact for the majority of our representations. Where does the power of scientific models – our particular interest here – to represent the world come from, if not from resemblance? We get a part of the answer when we pay attention to the fact that a model is the representation of a system, whose structure is what is represented. The part of perceptible phenomena which is represented by a model does not include the sensations that phenomena make us feel, but only their structure (or some substructure of that). Resemblance is not helpful in order for the model to conform to the structure to be represented, but only *isomorphism.* There is isomorphism when the specifications of the model correspond to the specifications of the structure which is represented. For example, every subset of the model, and every relation which connects them, must have corresponding to it a subset and relation in the represented structure, and the subsets and relations must have the same specifications.

We thus see, at the outset, that the absence of perceptible resemblance between models and reality is quite compatible with the realism of these models. It is sufficient to recognize that reality itself is not limited to our sensations, or to what is perceptible in the phenomena (reality is not limited to 'sense data'). The structure of phenomena is just as real as the sensations we get from them. As for the constructed character of scientific models, this is also compatible with realism, since the only thing that counts when deciding if a model is realistic or not, is that it should be isomorphic with the structure to be represented. This isomorphism is rarely complete, of course, since the model emphasizes some specifications of the system and neglects others.

# 4 Three conceptions of scientific activity

Does scientific activity consist in describing phenomena and obtaining accurate representations of them with the help of models? Alongside this conception of the work of the scientist, a conception quite current today which draws inspiration from empiricism – though empiricism is richer and more subtle than the current conception – there is another, also a current position, which draws inspiration from operationalism. For this latter, science is akin to technology, both being attempts to model material and intellectual arrangements in order to be able to act on phenomena through them. For my part, I should like to insist on the fact that scientific activity – and thus scientific modelling also – is not limited to the description of phenomena (including the description of their observable structures[1]), nor to technology. Science also seeks to discover the structures, underlying phenomena, which govern the phenomena.

The three conceptions I have mentioned each reflect part of the work of the scientist – and thus part of the work of modelling as well – and so none of the three is false. It is desirable, I think, to see them as complementary rather than to set up in opposition to any one of them. The description of phenomena and the elaboration of technical capabilities are broad avenues of scientific progress. But the task at hand, which consists in searching for the underlying structures which govern and thus explain phenomena[2], should not be obscured by emphasis on observation or technical know-how.

Someone who thinks that science has no other task than to furnish accurate representations of phenomena has, paradoxically, good reasons for thinking that no scientific model can represent reality. For sooner or later, he becomes aware that there are multiple points of view on phenomena. He ought to select the subsets and relations which

1 Structures are never *sense data*, but observable structures do exist. For example, through observation we find out about statistical correlations, although the correlations are not sensations.

2 For an in-depth examination of the ways in which structures determine phenomena, and determine them in non-causal ways, see R. Franck 2003 pp.187-194.

will play a role in his model from among many more, while the greatest part of the phenomenon which he is trying to describe will be left to one side. How can one in this position not conclude that our models, influenced as they are by our own preferences and preoccupations, and involving our deliberate turning away from thousands of possible points of view and observations, are not simply the product of one's own thinking, not the accurate representation of some reality? The same conclusion arises for the one who identifies science with technology. From this viewpoint, the efficiency of the technology worked out determines whether or not a model is good. In both cases usefulness is held up as the only criterion for evaluating models.

The question of the realism of scientific models and their role in contemporary science takes on a different aspect when we admit that science also has the job of discovering the structures which underlie phenomena, and which govern them and furnish explanations for them.

## 5 Modelling the mechanisms of a system vs. modelling its properties[3]

In medicine we may find ourselves ignorant regarding the process within the organism through which a particular remedy acts on an illness. Nevertheless we may observe in systematic fashion the effects which the remedy produces in patients who have different illnesses, who are of different ages, etc. Statistics are a powerful tool for carrying out such observations. Now, finding out how the human organism reacts to a given remedy under different conditions is tantamount to discovering certain properties of that organism. If the doctor knows about these properties, he or she can decide which remedy is proper for the given patient, according, e.g., to the patient's age, or to his other illnesses, etc. Traditional medicine worked just this way, although today doctors take more care than formerly to observe the effects produced by a particular remedy in a systematic

3 Section 5 here is adapted from R. Franck 2002, pp.90-92.

way. In the 19th Century, such a practice in medicine was termed ‘empirical’ to distinguish it from the ‘scientific’ medicine which was in its infancy. A new form of medicine took responsibility, unlike its predecessor, for explaining the effects produced by medical remedies, and also attempted to explain the effect of pathogens on the organism. The method was to discover intra-organic mechanisms through which causes or inputs (pathogens and remedies) produced their effects or outputs (the appearance or disappearance of symptoms). Following the distinction between empirical and scientific medicine, the discovery of the properties of the human organism, thanks to systematic observation of effects produced by pathogens and by remedies – including the statistical tools which such observation employs – is sub-scientific (C. Bernard, 1966, p. 297-98). From this point of view, science only begins when we ask ourselves about the mechanisms which may explain observed properties, that is, mechanisms which explain why causes produce the effects they produce within the system under examination (in this case, intra-organic mechanisms).

This example from the developing practice of medicine in the 19th century is very suggestive. But the conception of science it illustrates can be applied to any discipline: are we satisfied when we have modelled the properties of a system? Or are we intent on modelling the mechanism within the system, which would allow us to explain its properties?

We may represent to ourselves the distinction between mechanisms within the system and properties generated by it with the help of the metaphor of the black box.

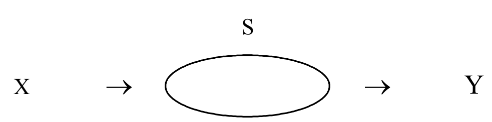


Figure 1

The mechanisms which generate the properties of the system (S) are inside the box. As long as we don't know what's inside the box, we call it 'black'. The properties of the system are outside the box. These are the outputs (Y) which issue from the box when certain inputs (X) occur. No input, no output. We must be careful not to try to define the properties of the system by its outputs alone. A property of the system is that particular kind of output which the system can generate when it receives a particular kind of input. Another system might generate a different output in response to the identical input. And the same system may generate a different output when it receives a different input[4]. The properties of the system must, therefore, be defined according to a pairing of inputs and outputs (X,Y) which is operated by the system. In short, let us define properties as the specific effects that may be produced by the system in interaction with a definite environment.

The metaphor of the black box (which is undoubtedly an imaginary system!) helps us understand the advantage of differentiating the phenomena we observe in this way: some belong to the system's mechanism, while others belong to the properties of the system that are generated by the mechanism. If we don't mark this distinction, we risk confusing a mechanism with its properties in our model when we try to model a series of phenomena. We even risk mixing up within our model fragments of different, unidentified mechanisms, and fragments of properties of different mechanisms[5]. Let's hold on, then, to the idea (in response to our questions about the

4 Taking this into consideration, we can see that the outputs of a given system have a double origin. One origin is the set of inner mechanisms within the system which generate outputs; but the factors, external to the system, which provoke the outputs, are another origin. And we also see that we may have recourse to two different types of explanation in order to explain the outputs of a system: we can explain these with reference to the factors which are external to the system and which provoke outputs, but also with reference to the mechanisms interior to the system which generate the outputs. Finally we now see that each type of explanation, taken separately, is not sufficient, because the outputs of a given system can vary with its inputs, and because the effects of a given input can vary with different systems. The notion of causal explanation is turned upside down by this point of view (see R. Franck 2003, pp. 184-186).

role of modelling in today's science) that the modelling of phenomena can move in two directions: the modelling of properties, and the modelling of the mechanisms for a given system.

## 6 Empirical models and formal models

We shall now see that the process of modelling mechanisms can also move in two directions. A mechanism has a material structure and a formal structure. The material structure is made up of a network of empirical relations obtaining between empirical subsets; in other words, these subsets and their relations are accessible through observation and/or experience. The solar system, as modelled by Kepler, is a famous example. But the solar system possesses another kind of structure, which was modelled by Newton. The law of gravitation, and the principles upon which it rests, do not represent an empirical structure. This law establishes a network of formal relations between concepts. It represents the formal structure of the solar system. And since Newton's model, as opposed to Kepler's, is not made up of empirical subsets and relations, but of formal subsets and relations, it can be applied to gravitational systems other than the solar system.

I began by saying that a scientific model represents a system, and that it represents the system's structure. We can now complete that statement. An empirical system has three kinds of structure. First, the empirical structure of the properties of the system. Second, the empirical structure of the mechanism which generates these properties. Third, the formal structure of this mechanism. The scientific model can represent any of these three structures of the system.

I suggest to call models 'formal' when they represent the formal structure of the mechanism of a system, and 'empirical' when they represent empirical structures, either of the mechanism or its properties. Strictly speaking, it is not the model itself which is formal

5 This is a burning question in the social sciences. I attempted to deal with it in R. Franck 2002, p. 93-98.

or empirical, but the structure which it represents. For example, a model expressed in formal language is still empirical if it represents the empirical structure of the system[6].

## 7 Artificial models

Can we learn something about a natural object or process by analyzing the structure or the functioning of an artificial device built for the purpose of reproducing the behaviour or the performance of that object or process? This question was asked by Massimo Negrotti last year in the introduction chapter to the first volume of the Yearbook of the Artificial. I will conclude this introductory chapter with a look at the question of the fruitfulness of artificial models in science. The method to which Negrotti refers has been used in research concerning artificial intelligence (AI). It has later been used in other domains, such as biology and economy. The devices can be virtual, that is, constructed by computer simulation methods. The computer model will be adjusted little by little to produce a better fit between its results and results generated by the natural system. When the fit is good enough, we suppose that the structure of the computer model is isomorphic with the structure of the natural system. And following this hypothesis, the model teaches us something about the natural system's structure.

The artificial device can be virtual, but it can also be material. The last is the kind of device for which Massimo Negrotti uses the term, 'technology of the artificial'.

> The interest for a general understanding of the artificial comes, therefore, from the persuasion that to *produce* something *ex novo* (let's name this *conventional technology*) is a quite different affair than *reproduce* something existing in the nature (let us name this *technology of the artificial*). […] the technology of the artificial is devoted to replace natural *exemplars* with man-made substitutes able to exhibit some *essential performance* of them. (Negrotti, 2002, pp. 10-11).

6 The difference between empirical and formal models has been closely examined in R. Franck 2002, in the Conclusion of Part III.

Negrotti doubts that material devices can teach us anything about the natural exemplar whose performance they ape in some respect. Let's look closely at his argument.

An artificial device involves the use of materials which are different from those nature has used. The materials to be used in the construction of the artificial device enter the process with certain properties and qualities of their own. And unexpected internal interactions among the properties of the newly chosen materials can generate unforeseen side effects. Moreover, an artificial device cannot reproduce a natural exemplar in its entirety. Some observation level is selected in accordance with the particular performance or behaviour of the natural exemplar which one wishes to reproduce. Negrotti concludes that while the core of an artificial device has to work in a manner similar to some particular natural thing, a number of further properties or performances, either actual or potential, may be activated suddenly by a variety of causes at several different observational levels. This is what Negrotti calls 'the unavoidable *transfiguration* of the *exemplar* and of its *essential performance*', brought about by the artificial. (id.p.14)

The use of materials which are not the same as those which make up the natural exemplar, and the fact that the artificial device only reproduces a small part of the real system, leaving aside many possible interferences related to the multiple levels on which the real system may function – all this should convince us that the mechanism operating in the artificial device is often quite different from the mechanism of the natural system. And in this respect Negrotti is right when he says that the artificial device cannot teach us anything about the natural system.

Here are two examples which support his position. Armand de Callatay (2002, p. 108) writes:

> If an artificial heart is grafted to a patient, this heart is an engineering model of the natural heart. This heart uses different pumping principles. It does not use the energy molecules produced by the body. It does not self-repair nor adapt its size to the efforts required as a natural organ does, and it will not self-reproduce. It requires anti-coagulants in the blood. It performs anyway the same function.

In this example two materially different structures achieve a same performance. In a similar manner, we may note that it is unnecessary for a computer to resemble the human brain in order to mirror some of the properties of the brain. Thus in a general way we may state that similar performance may be achieved using different materials. And we may add that the same performance may be achieved through different mechanisms.

But an empirical system possesses three kinds of structures, as we noted. Apart from the structure of the properties of the system, the mechanisms of the system have both a material and a formal structure. A computer does not have to copy the material (neuronal) structures of the brain in order to mirror some of its properties, but doesn't the computer have to mirror the formal structure of neuronal mechanisms which governs the particular performances of the brain?

Under this hypothesis, the answer to Negrotti's question bounces back toward us. The artificial device does not teach us about the empirical structure of the natural system whose performance (in some respect) is reproduced by the device. But the artificial device can help us find out the formal structure of the natural system. It can help us do that if it is true that in order to produce identical performance, two different systems must possess the same formal structure, even though their mechanisms may operate with empirical structures which are different. In other words, two different empirical structures which produce identical performances should possess the same formal structure. This point of view reinforces our intuition, widely shared, that artificial devices, both virtual and material, are after all a good way to learn about natural systems[7].

If the point of view which I have just put forward is correct, the advantage provided by artificial devices, both virtual and material, is that they allow us to find out the formal structure of a natural system without knowing its empirical structure. They allow us to find out the

7 If the artificial neural networks (ANN) are 'blind', as is sometimes said, because they are not constructed from knowledge of natural neuronal mechanisms, still they may be able to help us – if the hypothesis we are working under is correct – to uncover the formal structure of neuronal mechanisms. This is what I tried to show in R. Franck 2002, pp. 142-145.

formal structure of the system without having to open the box – to return to the metaphor of the black box. In what way? The model – more precisely the formal structure of the artificial device, whether virtual or material – can be adjusted little by little so that its results match those of the real system better and better, as I recalled just above. When the results match well, we can maintain – if the point of view I am supporting is correct – that the formal structure of the computer model or of the material device is isomorphic with the formal structure of the natural system. Thus, it is the results, that is, the properties of the system, which guide us in the figuring out of its formal structure, with the help of an artificial device. Such a procedure does not seem different from some types of experimental control. And it justifies our going even further in the use of artificial models in scientific research, provided that we specify what knowledge we expect their use to yield (see Burch 2002, pp. 245-265).

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