透過可落實模型來檢驗科學理論

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摘要

像古典力學一類的科學理論如何被檢驗？這個問題有個長遠的歷史。在本文中，我將提議一個檢驗理論，建基在吉爾關於科學理論結構的研究上。但我的模型觀點與吉爾有些微不同。我將從理論性和歷史性兩個不同角度來展示：科學理論總是可以被理解為擁有一個分類的模型體系的理論，其中包括高層的模型與可落實模型；而且科學家總是透過可落實模型來檢驗理論。但是，透過可落實模型把檢驗的結果傳送到高層的模型或原理，乃

是一件非常複雜的機制。因此，就算有一些可落實模型被印證或否證，整體理論完全被印證或否證實際上不太可能。最後，我將以說明牛頓理論的檢驗史為例，來佐證本文提議的檢驗理論。以拉卡托斯的話來說，這個檢驗理論在本質上也是個針對歷史的「合理重建」。

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Testing through Realizable Models

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Abstract

How is a scientific theory, especial a classical physical theory, tested? This problem has a long history. In this paper I'll propose a theory of testing based on but differentiated from Giere's studies on the structure of scientific theories (Giere 1988, 1994, 1999). I will show, from both theoretical and historical perspectives, that a scientific theory can always be understood as one contains a classified model population, including both higher-level models and realizable models, and that scientists always test a theory through its realizable models. To transmit the consequences of testing realizable models to a higher-level model is a very complicated mechanism. Therefore, it is unlikely that a whole theory could ever be completely confirmed or falsified, even if some of its realizable models have been conclusively confirmed or falsified. Finally, I'll illustrate such a theory of testing can give an adequate account of the testing history

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of a scientific theory, for example, the Newtonian theory. This theory of testing is a rational reconstruction, in Lakatosian sense, of the process of scientific testing.

Keywords:

philosophy of science, test of scientific theories, model, realizable model, confirmation

Testing through Realizable Models*

How is a scientific theory, especial a classical physical theory, tested? This problem has a long history. Its solution involves the question of what a scientific theory is. What structure does a scientific theory have? In Chen's work, "Theory Versions Instead of Articulations of a Paradigm" (Chen, 2000), he proposed the notion of a *theory version* as a replacement for the Kuhnian notion of articulations of a paradigm. He proposed a characterization of the conceptual (i.e., categorization-and-taxonomy) structure of theory versions and discussed the taxonomic hierarchy of subjects in theory versions. Given the results of that paper, the problem of testing theories becomes: How can a theory version having such a taxonomic structure be tested?

Traditionally, this problem also concerns the confirmation of scientific theories. It concerns the relation between a theory and the objects it explains, that between a theory and experiments, and that between a theory and the evidence supporting it. One traditional

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approach to the topic is Bayesian. Scientists and philosophers who accept this approach seem to believe that a theory should be confirmed by *inductive* or *statistical* ways. When a phenomenon predicted by a scientific theory is observed, it counts as a confirming instance for that theory. A theory is confirmed to a high degree only if it accumulates many confirming instances. This approach has, however, been criticized from a number of different perspectives[1].

The *semantic view* treats the problem of confirmation as part of the issue of the relation between a theory and phenomena — specifically, how to fit the structure of a theory onto the structure of experimental data[2]. On this view, theory confirmation is no longer completely a matter of induction and statistics of instances; it involves many complicated experimental processes, designs, and

1 For example, Karl Popper from the falsificationist view; the philosophers such as Kuhn and Feyerabend from the historical approach; and philosophers such as Suppe (1989, pp.348-413) and von Fraassen (1980, pp. 132-134) from the semantic view.

2 This is a Suppesian locution (Suppes, 1977). For van Fraassen (1980), the answer to the problem is an isomorphism between theory structure and appearance structure, for which he developed a probabilistic account. Giere (1988) thinks the answer is similarity between a model and a real phenomenon; the similarity is asserted by a theoretical hypothesis. Suppe (1989, pp. 133-146) proposes a detailed but complex fitting-theory. He considers the problem of confirmation as a part of the problem of the relation between a theory and phenomena and characterizes the confirmation of a theory as the application of a theory to the relevant phenomena. The answer involves items such as experimental equipment, instruments, a process of data-collecting, and measurement. In applying theory to phenomena, scientists have to develop a theory of experimentation, including *ceteris paribus* conditions, a theory of experimental design, and a theory of data.

concepts. In particular, theory structure or models serve as intermediaries in the search for a fit between theoretical computation and experimental data.

But can a scientific theory version in fact be confirmed or falsified? Historically minded philosophers of science have shown convincingly that the answer to this question is *No*. Even if we accept the semantic view that there is a good or bad fit between theory structure and the structure of empirical data, this fit is not sufficient for us to answer whether any whole theory in scientific history was completely confirmed or falsified.

In this paper I will show, from both theoretical and historical perspectives, that any theory or theory version contains a classified model population, including both higher-level models and realizable models, and that scientists always test a theory version through its realizable models. To transmit the consequences of testing realizable models to a higher-level model is a very complicated mechanism. Therefore, it is unlikely that a whole theory version could ever be completely confirmed or falsified, even if some of its realizable models have been conclusively confirmed or falsified. Consequently, the highest model as a theoretical principle, in a theory version remains unconfirmable and unfalsifiable. Finally, I'll illustrate such a theory of testing can give an adequate account of the testing history of a scientific theory.

Here I attempt to develop a theory of testing in the sense of theory as model, that is, to construct a conceptual model for scientific testing. I don't try to discover the actual testing process in scientific researches, neither I am suggesting a normative requirement for scientific testing. What I reveal is the "inner logic," in Popperian words, of scientific testing under the new understanding of a physical theory contains a model population. What I do in this paper is a rational reconstruction, in Lakatosian words, of the process of scientific testing.

1. Types of Models

On the semantic view, a model can be identified as what is described by scientific laws or statements. But what is a model in a general sense? What does the term "model" mean as used in science and in everyday life? What are the general features and structure of scientific models?

Some philosophers, such as Max Black, have analyzed the ordinary meaning of "model" in English, where "model" is typically used to refer to "substantive models" of various scales. As Black says:

> Typical examples of models in the literal sense of the word might include: the ship displayed in the showcase of a travel agency ("a model of the Queen Mary"), the airplane that emerges from a small boy's construction kit, the Stone Age village in the museum of natural history. That standard cases are tree-dimensional miniatures, more or less "true to scale," of

some existing or imaged material object. (Black 1962, 219)

Here we might speak of "substantive models" as typical or prototypical examples not only in our everyday use of "model" but also in scientific use. When models are considered in this way, we immediately think of models of many types that are used in science and engineering, such as the H_2O molecular model, the solar system, dams, motors, and other items. But this isn't the only sense of "model" in ordinary life and science[3].

Scientists frequently refer to a non-concrete object such as an imagined image, a picture or icon, a conceptual description, or a mathematical construct as a "model," because they use these entities to represent, imitate, or analogize the structure or behavior of some kind of object or event. This implies that in scientific practice, models are not a single kind of thing, but a family of different sorts of things. Philosophers of science have tried to characterize and classify models in various ways on the basis of the role and function of models in scientific theories. For some earlier philosophers, such as Nagel (1961) and Hesse (1966), the major function of models is *analogy,* which supports an inferential relation between the structure of the model and the modeled object or phenomenon. Black (1962) and Achinstein (1968) developed a more complete classification of types of models in philosophy of language and philosophy of science, respectively. Since

[3] In Black's analysis, the other usual senses of "model" are a type of design (e.g. the dress designer's "winter models") or something worthy of imitation (e.g. a model husband). (Black, 1962, p.219)

model theory arose as a subfield of formal logic in the 1960s, a new, supposedly more fundamental sense was injected into the concept of a model. Working with the notion of a model in the sense of formal model theory, Suppes (1957, 1961), Sneed (1971), van Fraassen (1970, 1980), and Suppe (1989) developed a *semantic view* of scientific theories[4]. Despite differences in approach, terminology, and detailed claims, these writers all share the view that a model or structure is the heart of a scientific theory[5]. They all seem to hold that all types of models can be reduced to models in the sense of model theory[6]. But this set-model-theoretical reduction may have little relevance to the actual application and evolution of models in scientific history. Moreover, it is a purely extensional approach, which neglects the intensional and taxonomic aspects of scientific theories[7]. If we want to

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4 On this view, the heart of scientific theories is not the written sentence, as the traditional philosophers claimed, but an abstract construct called a structure, a state space (Van Fraassen's technical term) or a model (in the logical sense). A model in the logical sense represents the abstract structure of a group of objects and is assigned to a set of sentences as its semantic content. The set of sentences characterizes the behavior of a group of objects. Models in this sense usually include a set of objects (the domain), relations and functions, and are logically expressed as an ordered tuple, i.e., $<D; r_1, r_2, \ldots, r_n; f_1, f_2, \ldots, f_n>$.

5 Suppes and Sneed take an axiomatic approach to scientific theories and formulate an axiomatic system specifying their logical structure. Von Fraassen and Suppe abandoned the axiomatic method and devoted their attention to the semantic structure of scientific theories. Chuang Liu (1997, 1998) has presented a hybrid formulation.

6 Cf. Suppes (1961), pp. 163-168, and Da Costa & S. French (1990), pp. 258-260.

7 Suppes(1957) had presented an axiomatic system of the classical particle mechanics through set-theoretical method. In Seend's view, the method can

consider actual scientific theories and actually applied models in scientific history, we cannot regard models in this reductionist sense as the standard notion of a model.

Since the reductionist approach is unsuitable for exploring models in the sense I am concerned with here, I will observe up front that in scientific practice various types of models are used, and new types of models are likely to be developed in the future. When new types of models are invented (e.g., computer models applied in scientific simulations), it is necessary to construct a new taxonomy of types of models. I suggest that the notion of a model should be understood in terms of a taxonomy of types of models.

Roughly speaking, models always involve a certain relation between two things—specifically, one of the two things represents, imitates, analogizes, or simulates the other. We can call this very general relation "modeling"; all representing, imitations, analogizing, or simulating are then specific types of modeling. Representing is modeling by mirroring appearances or by one-to-one correspondences. Analogizing is static or structural modeling. Imitating is behavioral, procedural, or evolutionary modeling. Simulating is procedural, dynamical, or even digital modeling. Given

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be reduced a form of sentence: X is an S. Where both X and S are variables. X represents a model and S represents a undefined theory. Let $X= <D; r_1, r_2,\ldots, r_n ; f_1, f_2,\ldots, f_n>$, then $<D; r_1, r_2,\ldots, r_n ; f_1, f_2,\ldots, f_n>$ can be used to define S. The model X as such are defined by several axioms expressed as symbolic formulations. An interpretation of the signs and axioms is an assignment of objects that can satisfy those axioms. It doesn't use network of categories and a hierarchy of kinds to interpret the signs in the axioms of scientific theories.

a modeling relation, the item that models the other is the model, and the modeled item is the modeled. So here we have a general structure for models consisting of four basic items: the model, the ontological status of the model, specific types of modeling, and the modeled item. A table including a classification of types of models can be constructed according to this general structure. See Table 1.

Table 1 ，貼上 PDF

The basis for the classification in the above table is ontological status. That is, each type of model has an ontological status different from the other types. But another potentially useful classification would be one whose taxa are specific types of modeling relations. Every type of modeling relation has several likely subtypes. Thus, we can build a taxonomic tree for types of modeling relations on the basis of the differences between such subtypes. See Fig. 1.

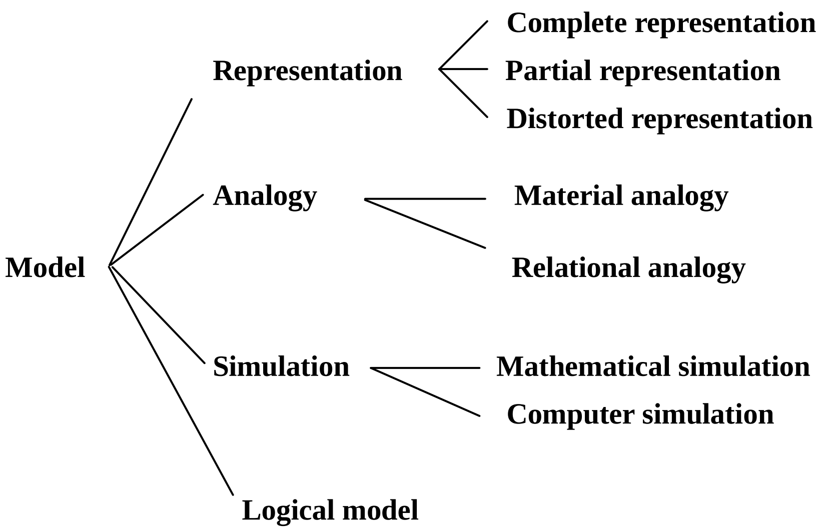

Fig. 1

In the following, references to models in science or to scientific models are not intended to refer to any specific type of model. Working scientists in actual history have probably applied all the types of models in the above two classification schemes, and perhaps others as well. A single phenomenon is likely to be modeled by different types of models, as when DNA is modeled by substantive models, iconic models, and computer models. All types of models serve as an intermediary linking scientific statements or formulas to the modeled phenomena or systems of objects.

2. Models and Taxonomy

In Chen's "Theory Versions," he argued that categorization and taxonomy are two types of organizational patterns of scientific theories. Categories and kinds inform us about similarities and differences between objects in the world. If one has a conceptual system corresponding to a system of categories-and-kinds, then he has "conceptual" scientific knowledge—that is, knowledge of the qualitative relations between concepts. But such a conceptual system obviously doesn't cover the entire range of scientific knowledge. Scientific disciplines seldom seek only knowledge of a qualitative system of categories-and-kinds. Rather, scientists value quantitative links between categories (that is, scientific laws) and explanations of phenomena. A system of categories and kinds is only the byproduct of such links and explanations.

Categorization does involve the formulation of scientific laws, because categorization is not only classification of categories but also definition of categories. To define a category, it is necessary to appeal to other categories and to connect them into a network of categories. A network of quantitative links is implicated in the categorization by the construction of scientific laws.

However, to achieve the other main aim of scientific inquiries—the explanation of natural phenomena—we must actually apply scientific laws to explain phenomena. How do laws explain phenomena? Through models: scientific laws present models for phenomena. More specially, the models described by laws have an inner structure that reflects the structure of phenomena or the behavior of the things explained. The relations between laws, models, and explained phenomena can be pictured as shown in Fig. 2.

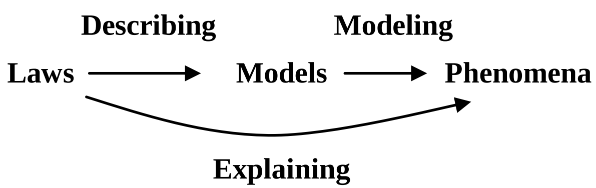

Fig. 2

The models described by the laws in a theory are organized into a hierarchy of taxonomic models—in Giere's words, a family of model families or a model population (Giere 1994, 1999). For example, the hierarchy of models in Newtonian mechanics can be pictured as shown in Fig. 3.

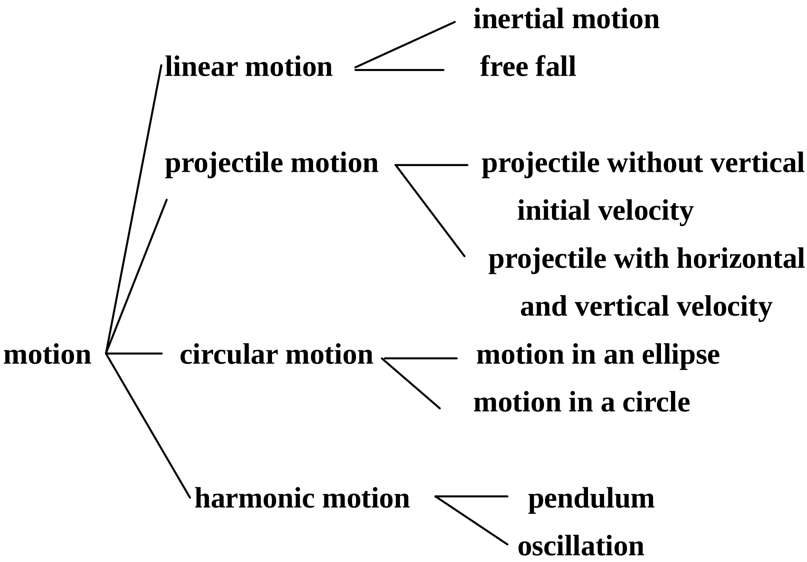

Fig. 3

Every item in the tree is a model-kind. The models on a branch are subkinds of the models on the trunk from which the branch stems. Newton's second law is conceived of as unifying all the various model-kinds. So it plays the role of a theoretical principle in this taxonomy of models. How does it fill this role? Scientists derive various theorems or formulae from Newton's second law according to the features the type of motion explained. If the path of a body is a straight line, the direction of impressed force is the same as or opposite to the direction of motion. If an object is thrown in a horizontal direction, the impressed force should be analyzed into horizontal force and vertical force, and so on. On the basis of these features, scientists posit different functions of force or functions of position and then derive different theorems of motion. The different functions that are posited depend on how various categories (force, position, etc.) are reclassified. Newton's second law can be analyzed into a hierarchy of theorems of motion, which is isomorphic to the hierarchy of models. The following diagram (Fig. 4) shows a hierarchy of Newtonian dynamical theorems[8].

- **F=ma**
  - **F=ma (linear motion)**
    - **W=mg (free fall)**[9]
  - **F_y=mg; v' (projectile)**[10]
    - **Fy=mg; $v'_t = 0$; $v'_h \neq 0$**
    - **Fy=mg; $v'_t \neq 0$; $v'_h \neq 0$**
  - **F(r)= - kr (circular motion)**
    - **r''+kr=0 (motion in an ellipse)**
    - **$\theta''+\omega_0^2\theta=0$ (motion in a circle)**[11]
  - **F(x)= - kx (harmonic motion)**
    - **$\theta''+\omega_0^2\theta=0$ ($\theta<90°$) (pendulum)**
    - **$a+\omega_0^2x=0$ (free oscillation)**
    - **$a+2\beta v+\omega_0^2x=0$ (damped oscillation)**

Fig. 4

Every theorem corresponds to a model kind

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[8] Cf. Marion, Jerry B. & Thornton, Stephen T. (1988).

[9] Where W represents the weight of the free falling body at some certain place; and g represents the measurement of gravitational acceleration at the same place.

[10] Where v' represents the initially velocity of a projectile body; v'_t represents the initial velocity in the vertical direction and v'_h represents the initial velocity in the horizontal direction; F_y=mg represents the projectile body with a mass m is acted by a vertical gravitation F_y and F_y is equal to mg.

[11] Where r is a vector from the center directed to the particle's position; and θ is a angle between the vector r and X-axis; and θ'' is a second order derivative of θ; and $\omega_0 = 2\pi\nu_0 = \sqrt{(k/m)}$; ν_0 represents frequency and ω_0 angular frequency.

or a model family. The categorization of models into a hierarchy has an interesting implication: theoretical principles relate to phenomena not only through models, but rather through a hierarchy of models. For the models on the branches of hierarchy provide easier access to actual phenomena than those on the trunk. The models on the trunk are more abstract than those on the branches.

Thus the entire system of categorization, taxonomy, and models presents a complete picture of the structure of a scientific theory or theory version.

3. Models and Phenomena[12]

In a full scientific theory, such as classical mechanics, the way that the theory explains phenomena is by constructing a family of model families or a model population. All scientific theories have a subject—a certain kind of phenomenon—as motion is the subject of classical dynamics. In classical mechanics, the phenomenon of motion is explained by applying a model or model population over the phenomena. By speaking of "over" the phenomena here, I mean to emphasize the priority of theory and model population to phenomena[13]. When we speak of motion in the actual phenomenal

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[12] Nancy Cartwright (1983) developed a similar version as mine here but based on the distinction between theoretical laws and phenomenological laws. Her discursive style is quite different from my taxonomic approach, so I won't discuss her version here.

[13] Hansen (1965) has a similar remark: "….But sometimes the physicist is concerned with the system of dynamics, within which nothing

realm, we mean the motion of a certain object or system of objects. The variety of kinds of moving objects is uncountably large, as is the number of different types of motion. It is impossible for us to explain every motion of every object. So scientists attempt to find the order hidden in plural, complex phenomena. They reach this goal by designing a single model or developing a theory including a model population in which a taxonomically hierarchic order is implied. The taxonomic order can be seen as modeling the order of the actual phenomena. Through the hierarchic order, we can determine how many kinds of motion there are in the phenomenal realm. We can also identify various types of motion. What we usually think of as the name of an actual kind of motion is in fact the name of a model kind within a theory. For example, what we call linear motion, circular motion, or harmonic motion are model kinds, but not actual kinds. So a taxonomy of actual phenomena is constructed by reference to the taxonomy of models over those phenomena. See Fig.5.

	model kinds		**sample of actual phenomena**
	inertial motion	→	**sliding ice on a frictionless plane**
linear motion	**free fall**	→	**a falling stone from the top of a tower**

disconfirms the laws because they determine those types of phenomena to which the system can apply." (p. 103) The difference is that Hansen doesn't make his remark from the model view.

projectile —— projectile → a bomb thrown by a bomber
(without vertically initial velocity)

Fig. 5

In this regard, how does classical mechanics explain actual phenomena, such as the revolution of the moon around the earth or the revolution of a stone tied on a string held by someone’s hand? It does so by appeal to models of circular motion: Motion in an ellipse is applied to model the revolution of the moon around the earth, and motion in a circle to the revolution of the stone around a fixed point. Conversely, we can say that the moon revolving around the earth is a realized instance of motion in an ellipse, and the revolving stone is a realized instance of motion in a circle. A model kind having actually realized instances can be called a *realizable model.*

How does a model kind, such as motion in a circle, model a revolving stone on a string? First, the stone must be treated as a mere mass-point, that is, features such as its shape, size, and hardness must be ignored. Second, the string linking the stone to the fixed point must be regarded as a non-concrete connection, along which a centripetal force is exerted with the fixed point as center. Third, the length of the string from the stone to the fixed point is treated as the radius of the circle-orbit along which the mass-point runs. The model of a revolving stone on a string is that an imagined mass-point with a certain speed traverses a geometrical circle with a certain radius. Since the components of the model are imagined or abstract, we may well speak of the model as an abstract system of objects or a system of abstract objects. A modeling relation obtains between the system of abstract objects and the actual phenomenon of motion.

How can an actual system of objects qualify as a realized instance of a model? An actual system should be isomorphic to a given model in an ideal situation or near-isomorphic (or quasi-isomorphism) in a general situation[14]. That is, a near-isomorphism (near common structure) obtains between the model and its realized instance. In the abstract system of "motion in a circle," for example, most of the relevant parameters, such as the mass of the mass-point, the radius of the circle, the velocity of the mass-point around its orbit, and the central force, correspond to most of the measurable quantities involved in the revolution of stone on a string, such as the mass of the stone, the radius of the string, the speed of the stone, and the tensional force of the string. "Correspondence" here involves the equality of numerical values (quantity) and the correlation of concepts (quality). So the stone on the string is a realized instance of the model. What degree of correspondence between model and its realized instance is needed for the relation between the two to count as a near-isomorphism? This is a problem how do scientists actually make a decision. Here I don't and can't try to propose a normative criterion for near-isomorphism. It involves an understanding concerning the structure and operative

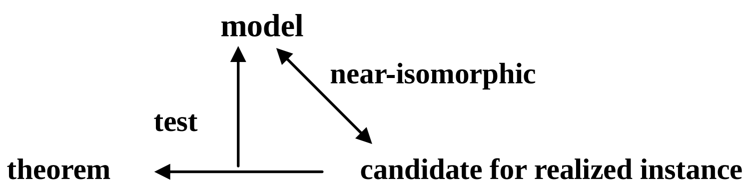
[14] Here the sense of "isomorphic" is as same as that in model-theoretical sense. But I don't claim that there must be a strictly, abstractly logical isomorphism between model and its realized instances. So I use the adjective "near" prefixing to "isomorphism" to form a new notion for fitting my requirement.

mechanism of experimentation. We cannot give a sufficient answer without inquiring scientific experiments. Roughly speaking, the working scientists would make such a judgment in accordance with the type of the subject, the level of experimental technology, and the development of theoretical instruments. To give a detailed answer to this problem, we have to consider the working, technological and social environment of scientists in history. Yet I attempt to suggest a “historical criterion”.

The “near-isomorphism” between a model and an object-system would occur, (a) while the working scientists recognize that they can no longer add any neo-parameter, neo-relationship or neo-function between parameters into the model and its theorem; (b) while that they can no longer exclude or separate any factor that does intervene the object-system by the current technology; (c) while they think that the errors between the quantities computed by the theorem and the measured quantities from the object-system are tolerable.

We should note that this isn’t in effect a normative criterion to which scientists make their judgment according, but a historical and situated recommendation which scientist endeavor to “realize”.

The explanation of phenomena and the testing of theories through models can be simply described in the following way. On one hand, different sets of numerical values or quantities can be assigned for the mass-point, radius, centripetal force, and period, and then the mathematical relation between them can be determined by a theorem describing motion in a circle. On the other hand, actual numeral data, including the mass of the stone, the length from stone to the fixed point, and the period, can be measured by observing the motion of the stone on the string and used to confirm or falsify the theorem. If the predictions or descriptions derived from the theorem agree with the measured data for or empirical descriptions of the candidate for a realized instance of the model, then the theorem is confirmed. If the two do not agree, then the theorem is falsified. Only if the theorem is confirmed can the model be considered realized and the candidate considered a genuine realized instance. The confirmation or falsification of the theorem is a test of the model itself. If the theorem is confirmed, then the model is also confirmed. If the theorem is falsified, then the model isn't realized, and the theorem or model should be corrected or modified. The following diagram (Fig. 6) shows the testing relation between model, theorem, and candidate for realized instance.



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\begin{tikzcd}
\textbf{\underline{confirmed} or \underline{falsified}?} \arrow[d] \arrow[dr] & \\
\textbf{model confirmed} & \textbf{not near-isomorphism} \arrow[d] \\
& \textbf{models or theorems corrected}
\end{tikzcd}
$$

Fig. 6

This scheme will be developed in more detail in the next section.

4. Simple and complex realizable models

Since a theory or theory version has a classified model population and a corresponding classified system of theorems, naturally higher-level couples and lower-level couples will occur in the hierarchy of models and theorems. Higher-level theorems that describe higher-level model families “contact” actual phenomena through lower-level theorems that describe lower-level model-kinds. The lower-level theorems explain actual phenomena through the mediation of the corresponding model-kinds that model those phenomena. For example, as a higher-level model family, linear motion has to be re-classified into lower-level model kinds such as inertial motion along a straight line, free fall and the like, so that it can “contact” actual phenomena through them. These model kinds obviously have realized instances that are near-isomorphic to them.

But there is no actual system of objects that can be a realized instance for a higher-level model family, such as linear motion. Unless the orbit and force of the linear motion are determined—such as a force-free mass-point moving along a horizontal straight line, a free-falling particle moving along a vertical straight line, or a thrown body moving along a parabolic line—we cannot find any actual system of objects that is near-isomorphic to the model family. But once these conditions are determined, they in effect classify the model family into several subkinds. We can say that, according to the classificatory order, a higher-level model family provides a more abstract model of the realized instances of its subkinds, but it in itself does not have any realized instances[15].

Generally, relatively lower-level model kinds or subkinds of a relatively higher-level model family are realizable models. However, many natural phenomena are so complicated that they cannot be explained by a simple lower-level model. To model them, we need a model combined with two or more lower-level models. These are not simple subkinds of a certain higher-level model family, but are still realizable models. We can call these *complex models*. A good example of a complex model in scientific history is Atwood's machine, designed by the 18th-century English scientist George Atwood (Greenslade 1985). A simple Atwood's machine is itself a substantive model consisting of two objects of different masses m

[15] In model-theoretical term, we can say those realized instances of the sub kinds are embedded in the higher-level model family.

and M suspended with an ideal string over a fixed frictionless pulley. When the supports of the two objects are removed, the object with larger mass falls, at the same time pulling the other object up. The theoretical model of Atwood's machine combines a rotating motion (the pulley), a descent motion with an upward force (the object M with the larger mass), and an upward motion along a vertically straight line (the other object m)[16]. This is obviously a realizable complex model. The theorem or formula describing the model is $a_s=g(M-m)/(M+m)$ where a_s is the acceleration of the whole system and g is gravitational acceleration.

George Atwood designed and built the experimental device known as Atwood's machine in 1784. He thought the measured acceleration of the two objects agreed with the computational outcome of Newton's second law of motion. Since Newton's second law predicted the experimental results precisely, it would seem to have been confirmed by experiments with the machine. Atwood said:

> The three physical propositions, having been assumed as principles of motion, reduce the science of mechanics to mathematical certainty, arising not only from the strict coherence of innumerable properties of motion deduced from them a priori, but from their agreement with matter of fact[17].

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[16] Of course, the rotating motion of the frictionless pulley isn't considered in mathematical analysis.

[17] From N. R. Hanson (1965), p. 102.

Is the second law of motion confirmed by Atwood's machine? Atwood's remark as such is correct, but he ignored the gap between empirical fact and principles. Newton's second law cannot be realized and confirmed directly by Atwood's machine and its experimental results, for the second law is a high-level principle from which a large population of models can be deduced or constructed. In light of the above analysis, what is confirmed by Atwood's experiments is the complex model and the formula describing it, not the second law of motion as such.

Cavendish's torsion balance is another type of complex model. It was supposed to test Newton's law of gravitation. The torsion balance consists of a light, rigid rod suspended by a vertical quartz fiber. Two small spheres, each of mass m, are mounted at the ends of the rod, and a mirror is fastened to the fiber. Two large metal spheres of mass M are put near the small spheres. If universal gravitation exists, then gravitational attraction of the large spheres acting on the small spheres will twist the fiber. We can observe whether a beam of light reflected from the mirror attached to the fiber is deflected by the mirror's rotation. Analyzing the structure of the apparatus, we find that a model for it combines linear movement over a very small distance, a rotating motion with a very small angle, and a light-reflection model from geometrical optics. The point of the apparatus is to test whether movement of the two small spheres causing rotation is observed. The deflection of the beam is only an auxiliary model, which assists us in observing the rotation of the mirror and in computing the magnitude of gravitation from the deflection. So does Cavendish's torsion balance confirm Newton's law of gravitation?

No, not directly or completely. The balance realizes linear motion caused by gravitational attraction of a small sphere over a small distance. But it doesn't realize other kinds of motion caused by gravitation—say motion in a circle or action over a long distance. That is to say, Cavendish's apparatus is not a realized instance of the relatively higher-level model of gravitation, but only a realized instance of the complex described above. Moreover, if we want to use experiments with the torsion balance to confirm the general formula of gravitation, say $G=gMm/R^2$, where g is the gravitational constant, we must already know the numerical value of the gravitational constant. But the torsion balance is treated by some university physics textbooks as an instrument for *determining* the numerical value of the gravitational constant[18]. In that case, Newton's law of gravitation is operating as a prior rule of inference, not as an empirical law to be tested.

5. Patterns of theory testing

For a long time, scientific theories have been specified from the positivist or falsificationist point of view as a set of statements or

[18] Cf, F. W. Sears, M. W. Zemansky, H. D. Young (1982), *University Physics*, p. 65.

formulae. Whether the theory is confirmed or falsified lies whether observational or experimental data support or refute empirical statements derived from the set of theoretical formulae that constitute the theory. The semantic view adds a mediating model between a theory and empirical data. The standard for confirming a model is isomorphism or similarity between the structure of the theory and that of the empirical data. But according to the discussion above, testing scientific theories (or theory versions) involves constructing realizable models and confirming the relevant theorems or formulae.

A theory version can be tested by finding or building realized instances. But before doing such tests, the scientist must construct realizable models—that is, derive lower-level model kinds from theoretical principles and higher-level model families, or construct complex models by combining several lower-level models. Once realizable models of a theory version have been constructed, there are two major ways to test them. (1) The scientist can find, in the phenomenal realm, some actual phenomena that are realized instances of the realizable models, or (2) she can manufacture material systems of objects that are realized instances.

The supposed aim of science is to uncover the structure of the natural world. Similarly, the aim of models is to model the corresponding actual systems of objects. If there are possible candidate systems, the scientist's task is to find an isomorphism between the candidates and the model. Is the actual system of objects near-isomorphic to the model? Is it in fact a realized instance of that model? If the empirical evidence concerning actual systems of objects provides an answer, then the model is realized. If it does not, then either the model must be abandoned or modified, or the empirical evidence must be re-examined. In general, if new phenomena are incorporated into the originally realized instance so that it is no longer near-isomorphic to the model, then the model is modified or supplanted by a new one that is near-isomorphic to the new set of phenomena. A new, modified model then has a newly realized instance that usually includes more phenomena than those modeled by its precedent. The best example of this type of situation is the gradual development, through a series of modifications, of the model of atomic structure. At the beginning of the 20th century, J. J. Thompson first proposed a plum-pudding model of the atom. In 1911, E. Rutherford suggested a new model that could explain the anomalies in his scattering experiments[19]. But questions emerged about the stability of the Rutherford atom, because its structure is similar to that of the solar system. These questions (as theoretical

[19] Thompson assumed that negative charges uniformly distribute in the volume of the atom with a positive charge. In 1909 to 1910, Rutherford and his students Hans Geiger and E. Marsden engaged a scattering experiment for investigating the inner structure of the atom. They bombarded a thin gold foil with a beam of α-particles emitted by a radioactive source and discovered an anomaly that some particles had a 180º deflection. See R. Brenann (1996), ch. 4, “Rutherford”. A concise reference, see any university textbook of physics, e.g., S. M. Lea & J. R. Burke (1997), *Physics: The Nature of Things*, pp.1119-1125.

consequences) together with the phenomena of Balmer's spectrum led to the development of Bohr's model of the atom[20].

The second way of moving from model to phenomena is to construct material or substantive systems of objects that are near-isomorphic to the realizable model. Scientists try to manufacture artificial systems of objects following the guidance of the model. The latter in effect becomes a "blueprint" for the manufacture of the former. If the system can be built successfully, then it serves as a realized instance of the model. The history of classical mechanics provides many examples of such systems, such as the manufacture of the ideal spring, ideal pendulum, and frictionless plane. Strictly speaking, a stone naturally swinging back and forth on a string is not an instance of simple pendulum, because there are too many variant correlatives, such as the irregular shape of the stone, air friction, and the elasticity of the string. But scientists can produce an ideal simple pendulum by excluding all variables that interfere with the system's being a realized instance of the model. Atwood's machine and Cavendish's torsion balance are also such artificial systems of objects. As can be seen, to fulfill their function, complex models designed to test the theoretical principles of

[20] To maintain the stability of atom and explain the quantitative features of Balmer's spectrum, Bohr introduced the concept of quantum (quantization of energy) into the orbit in which an electron moving around the nuclear. Bohr's model, of course, was modified or corrected by Schördinger's quantum mechanics. A theoretical, detailed exposition from Thompson's model of the atom to Bohr's, see R. Eisberg & R. Resnick (1985), *Quantum Physics*, ch. 4.

classical mechanics or other theories must be concretized or instantiated. If the actual physical systems successfully fulfill the predictions of the models, they become realized instances of the models. Strictly speaking, such constructed systems are not “natural” phenomena.

It is worthwhile to note that what we have been calling realized instances have traditionally been regarded as confirming instances of the tested laws or principles. But any realized instance presupposes or corresponds to a realizable model that is described by a theorem or formula derived from higher-level theoretical principles. So a realized instance is always an actual set of phenomena or a concrete system of objects that is near-isomorphic to the realizable system of abstract objects. Hence it is a confirming instance only for the corresponding model, but not one that can singly confirm any higher-level model or principle. A higher-level model will be confirmed only if all of its’ subkinds have been confirmed. In other words, because of the hierarchical structure of scientific theories, it is impossible for a higher-level model to be realized sufficiently.

Since a higher-level model family cannot be sufficiently realized, theorems describing it cannot be sufficiently confirmed or falsified. The higher-level model family can be tested only through its realizable submodels. Testing a higher-level model is thus a very complicated affair. There are several possible outcomes: (1) If all subkinds have realized instances and all theorems describing them are confirmed, then the model family is confirmed. (2) If all subkinds but one are realized, then the model family may be partially confirmed. Either the unrealized subkind must be modified, or the candidate for a realized instance of it must be re-examined. (3) If only relatively few subkinds are realized, then the model family and the corresponding theorem become problems or puzzles requiring more consideration. Either the unconfirmed subtheorems must be recomputed, or the measured data on the candidates for realized instances must be re-examined. (4) If all the subtheorems are disconfirmed, and therefore no submodel can be realized, then either the model family and its corresponding theorems must be corrected or modified, or the candidates must be re-examined. If the researchers find there are too many hidden variant factors in the natural circumstances, they are likely to try to construct ideal systems as candidates for realized instances. (5) If only one subkind has realized instances, then the model family is again a puzzle. Either scientists will attempt to realize the other subkinds or they will adopt the same route as in (4). (6) If no subkinds have candidates for realized instances, then either the model family is a purely conceptual model (e.g., as in some thought experiments) or all the subkinds need to be reclassified.

These six situations are merely a schematic sketch of the sorts of situations that may arise; they do not cover all possible cases. A more historically oriented consideration of the problem will be presented in the next section. But here we can sum up by saying that in most situations, a higher-level model family stands as a puzzle providing many problems for scientists to investigate in the process of what Kuhn called “normal science.”

A theory version contains at least one higher-level model family and usually more. Since a typical theory version contains several higher-level model families or even a multilevel hierarchy of models, testing it is even more complicated than the case of a single higher-level model just considered. Still, the basic scheme involved in testing a theory version does not go beyond the type just outlined. Logically, it is possible that all the higher-level model families of a theory version may be disconfirmed, with the result that the theory version is falsified. But in actual scientific history, it is unlikely that such a theory version would ever have been accepted to begin with, since it is unlikely that it could explain any phenomena at all. Probably, any theory version that has ever actually been studied has indeed yielded at least some realizable models. For only if a theory version has realizable models will scientists attempt to apply it to phenomena. On the other hand, it is unlikely that all higher-level model families studied in actual scientific history were confirmed, since for any given family there are almost always anomalies. In principle, the number of realizable models may be infinite, but in practice not all can be realized.

6. A testing history of Newton’s theory version

A Newtonian theory version including a taxonomy of model families and the realized instances of lower-level model kinds can be depicted as shown in Fig. 7

inertial motion ←→ Galileo's slope experiment
linear motion — free fall ←→ a falling ball, stone, etc.
projectile motion — projectile ←→ a flying bullet, bomb, etc.
circular motion — motion in a circle ←→ a revolving stone in a string with a fixed end
motion in an ellipse ←→ revolution of planets (the moon round the earth, the planets round the sun)
harmonic motion — pendulum ←→ Galileo's pendulum experiment
oscillation ←→ a variety of spring oscillations

Fig. 7

It's clear that most of the lower-level model kinds in the taxonomy have realized instances, and the corresponding theorems have been confirmed. This fact makes the Newtonian theory version irrefutable, despite the lack of fit between some models and their realized instances, say the orbits of Mercury and (at one time) Uranus. Of course, this irrefutability does not imply that the Newtonian version has been completely confirmed.

In actual history, how were Newton's own version in his *Mathematical Principles of Natural Philosophy* (in brief, *Principia*) and its expanded version (i.e., the Newtonian theory version) tested?

The testing history of Newton's version and the expanded Newtonian version can be reconstructed as comprising five stages: (1) Newton's own explanation of the confirmation of the three laws of motion. (2) The confirmation of celestial dynamics, including the explanation of the system of the world and the prediction of the orbit of comets. (3) Atwood's machine as a test of the second law of motion. (4) Cavendish's torsion balance as a test of the law of gravitation. (5) The discovery of Neptune as the great triumph of Newtonian celestial dynamics.

Newton, in his *Principia*, uses the three laws of motion as fundamental principles and demonstrates step by step how the whole system of the world is ruled by the law of gravitation. Newton claims the three laws agree with empirical facts and regards them as confirmed truths, attributing the confirmation to earlier scientific pioneers, especially Galileo. In the scholium to "Axioms, or Laws of Motion," Newton writes:

> Hitherto I have laid down such principles as have been received by mathematicians, and are confirmed by abundance of experiments. By the first two Laws and the first two Corollaries, Galileo discovered that the descent of bodies varied as the square of the time (in duplicata ratione temporis) and that the motion of projectiles was in the curve of a parabola; experience agreeing with both, unless so far as these motions are a little retarded by the resistance of the air. (*Principia*, p. 21)

Following this, Newton explains how projectiles confirm the second law. The projectile body is acted on by both an impressed force in the projectile direction and vertical gravitation. Suppose A is the starting point, where the body is thrown out. AB represents the distance traveled by the body in the projectile direction, and AC represents the descent distance of the body. The body moves along the curve of a parabola AED. ACDB forms a parallelogram. The second law can be confirmed according to the analysis of the parallelogram of forces (Ibid., pp. 21-22). As to the third law, Newton cited “the rules of the impact and reflection of hard bodies” established by C. Wren, Dr. Wallis, and C. Huygens. (Ibid., p. 22)

The second stage of this testing history is the confirmation of celestial dynamics. In the third book of *Principia*, Newton shows the agreement between his computations according to the theorems of the first and second books and the observational data for many celestial bodies. In addition to explaining known phenomena in the heavens, Newton makes a novel, exciting prediction about the orbits of comets in the third book. As astronomical historian Arthur Berry says, “This reduction to rule of the apparently arbitrary motions of comets, and their inclusion with the planets in the same class of bodies moving round the sun under the action of gravitation, may fairly be regarded as one of the most striking of the innumerable discoveries contained in the *Principia*.” (Berry, 1961, p. 238)

In "Proposition 40, Theorem 20" of the third book of *Principia*, Newton asserts that "the comets move in some of the conic sections, having their foci in the centre of the sun, and by radii drawn to the sun describe areas proportional to the times." This is followed by several corollaries: "Hence comets revolve in orbits returning into themselves, the orbits will be ellipse;" and "their orbits will be so near to parabolas, that parabolas may be used for them without sensible error."(*Principia*, p. 498) He then presents the computation of the parabolic orbit and cites the comets that occurred in 1680 as confirming instances of his theorems[21]. Halley worked out the paths of the comets occurring during 1680-1682 in accordance with Newton's principles. Struck by the resemblance between the paths described by the comets of 1456, 1531, 1607, and 1682, he conjectured that these comets were really different occurrences of the same comet at different times. This comet revolves around the sun in an elongated ellipse with a period of about 75 or 76 years. Halley successfully predicted that the comet would reappear in 1758 or 1759. The return of the Halley's comet stands as a great success of Newton's celestial dynamics[22].

[21] Newton himself prefers a remarkable comet observed by Halley in 1680. It has a period of about 575 years. He says, " The observations of this comet from the beginning to the end agree as perfectly with the motion of the comet in the orbit just now described as the motions of the planets do with the theories from whence they are calculated, and by this agreement plainly evince that it was one and the same comet that appeared all that time, and also that the orbit of that comet is here rightly defined." (*Principia*, p. 525)

[22] About the history of discovering Halley's comet, see Forbes (1990),

Newton himself believed the three laws of motion were empirical laws describing a variety of facts, and he believed they were sufficiently confirmed by empirical evidence. Did other scientists working with classical mechanics accept these beliefs? Not a few continental scientists in the 18th century tended to treat the three laws and even the law of gravitation as necessary truths[23]. Some great scientists in the 19th century regarded them as definitions[24]. This implies that they cannot be confirmed or disconfirmed.

Newton's fellow Englishmen Atwood and Cavendish insisted these four laws were empirical and could be tested experimentally. To this end, Atwood designed Atwood's machine and Cavendish the torsion balance. In carrying out their experiments, Atwood and Cavendish showed that they didn't agree with Newton that the laws had already been confirmed. The structure of their experimental apparatuses was analyzed in the above section. Did these experiments really confirm the principles of Newton's theory version? Atwood, Cavendish, and other scientists believed they did. If the

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Huges (1990), Waff (1990), Schaffer (1990). There were some questions concerning Halley's identification of the comet. Were they comets really the same? Why did the comet not have a stable period? Different models for the comet were proposed too. For example, a model of a couple of comets in a same orbit was suggested. Halley's own answer to the question concerning an unstable period was that the comet would be perturbed by the large planets such as Jupiter and Saturn.

[23] E.g. Euler, James Bernoulli, and D'Alembert, etc. See Dugàs (1988), Part 3, chs. 1, 3, 4.

[24] Hansen, in a footnote, cited also several scientists such as C. Maxwell, H. Poincaré, who view Newton's second law as a definition. (1965, p. 207)

experiments did so, then it is reasonable to say the four laws have been firmly and even irrefutably confirmed. But why did so many scientists disagree with them[25]? Moreover, even if Cavendish's experiment had been performed, Newton's law of gravitation still faced a crisis eventually: the anomalous orbit of Uranus.

The orbit of Uranus was a serious anomaly that created a great crisis for Newton's celestial mechanics. Newtonian scientists at the end of 18th century and beginning of 19th century did not abandon Newton's law of gravitation because of the empirical evidence of an anomalous orbit. Owing to their efforts, the puzzle and the crisis were eventually solved when Neptune was discovered. The original crisis became a great triumph for Newtonian mechanics (Abetti 1952, Grosser 1962). How did this occur?

A famous astronomer, W. Herschel, noticed a new star in the sky in 1781. Initially, Herschel thought it was a comet. Later, he recognized it as a new planet, Uranus, which revolved around the sun. Astronomers began to examine its orbit and the earlier records of its location. However, they found a disagreement between the observed

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[25] E. Mach thinks Atwood's machine is merely a method or instrument for verifying the law of free fall. (Mach 1961: 178) Some scientist thinks it is a device for measuring the value of gravitational acceleration. Hansen cited his words as follows, "Suppose we perform the above experiment and find experimentally a value for a which agrees with the predicted value….Does it mean that we have proved Newton's second law?….this question is absurd, since Newton's second law is a definition and hence incapable of proof….the Atwood machine is essentially a device for measuring the acceleration of gravity g by the determination of a rather than a set-up for the verification of Newton's second law." (1965, p. 101)

data and the theoretical computation of the planet's orbit. For nearly half a century, from 1781 to 1830, astronomers attempted to correlate various observed data and searched for the cause of the anomalous orbit, but all attempts failed. Uranus seemed not to be governed by Newton's law of gravitation. This phenomenon baffled all scientists who examined it.

What caused the unusual path of Uranus? Was there any factor that made the theoretical consequences of Newtonian mechanics disagree with the observed data? Or was it possible that Newton's law of gravitation was wrong? Newton's law had succeeded in many other cases: five planets, satellites, and comets were explained by it. There was no good reason for why the new planet should be an exception. After a long impasse, astronomers began to search for new solutions. During the decade from 1830 to 1840, at least five hypotheses (models) were suggested (Grosser 1962, pp. 46-49). Two challenged Newtonian celestial dynamics. One questioned whether the law of gravitation applied to objects as far from the sun as Uranus. The other tried to revive Descartes' vortex theory. Assuming the reliability of the law of gravitation, Newtonian scientists proposed the hypothesis that a new, undiscovered planet lay beyond the orbit of Uranus, causing perturbations in Uranus's movement. After 1840, when the other hypotheses were abandoned, the new planet hypothesis became the last hope.

If the hypothesis of a new planet was right, then astronomers faced the problem of how to compute its position. Only by computing the position theoretically could astronomers know where to look to observe the unknown planet. During 1845 and 1846, two young astronomers, J. C. Adam and J. Le Verrier, independently presented predictions about the position of the new planet. By September 1846 the observatory in Berlin had found Neptune.

The triumph of testing Newton’s theory version and the expanded Newtonian theory version took a pause after the discovery of Neptune. The next set of exciting achievements of science concerned the establishment and testing of electrodynamics, even though Newtonian theory had not yet solved the orbit of Mercury.

7. An analysis for the testing history

This review of the testing history of Newton’s theory version and the Newtonian theory version raises many questions. How should we treat Newton’s laws of motion and the law of gravitation? Since Newton’s four laws were supposed to have been confirmed by the first two stages, why did Atwood and Cavendish design new experiments to test them? When an apparent counterexample to Newton’s law of gravitation appeared and remained unsolved for decades, why didn’t many scientists reduce their reliance on Newtonian theory? Why did so many scientists regard the laws as non-empirical, e.g., as necessary truths or definitions? How could Newton’s laws agree with empirical data to such a high degree, if they were non-empirical?

On the view developed here and in my previous paper, Newton's laws should be qualified neither as empirical laws nor as necessary truths or definitions. Rather, they are highly abstract models, which comprise an elementary categorization and an immense model population. Newton's three laws of motion, above all the second law, stand in the place of principles, i.e., the highest-level model family, in Newton's or the Newtonian theory version. The law of gravitation is a higher-level model family. Free fall motion, projectile motion, motion in a circle, and other types of motion can be classified and derived out of the second law and the law of gravitation in order to access actual phenomena. To test these theoretical principles, scientists can seek simple realizable models or combine complex realizable models from lower-level models. Once realized instances for the realizable models have been found, if the measured data for these instances agree with the relevant theorems, these models count as realized and confirmed. Free falling bodies, projectile bodies, the orbits of the five planets, the orbits of comets, Atwood's machine, Cavendish's torsion balance, and the perturbed orbit of Uranus caused by Neptune—all are such realized instances. These all presuppose realizable models: free fall in a vertically straight line, projectile motion in a parabola, the elliptically orbital motion of the five planets, the motion of comets in a elongated ellipse, the complex motion of Atwood machine, the complex motion of torsion balance, and the perturbed motion of Uranus. What are empirically confirmed are these realizable models, not the higher-level model family, let alone the theoretical principles. That is, the so-called high degree of agreement between laws and empirical data is in fact an agreement between lower-level theorems and measured data and a near-isomorphism between lower-level realizable models and their realized instances.

Even if all subkinds were realized and confirmed, the higher-level model family (e.g., linear motion) would be merely indirectly, not directly confirmed. In fact, the actual phenomena are always more complex and complicated than the realizable models, so that most higher-level model families cannot be often confirmed even indirectly. Scientists must tolerate minor errors between actual phenomena and models, or they will confirm nothing. But they often feel dissatisfied with other researchers' confirmations: either they feel the errors aren't minor enough or the actual phenomena are far more complicated than those supposedly confirmed models. This is why scientists frequently attempt to design different experiments to test supposedly well-confirmed theoretical principles. Conversely, recognizing that higher-level model families such as linear motion and circular motion have so many realizable models with their realized instances, scientists tend to become firmly committed to Newton's four laws. Even when a serious anomaly arises, such as the anomalous orbit of Uranus, scientists (or at least Newtonian scientists) tend not to view it as a counterexample to the law of gravitation. Instead, what is disconfirmed or falsified is some realizable model of Uranus' motion and its theorem, i.e., circular motion without perturbation and its formula including a *ceteris paribus* clause. Even had the primary model of Uranus' motion been disconfirmed, Newtonian theory version has a scope for the modification of the model. The higher-level model family, say the general model of planet motion, is not disconfirmed for the disconfirmation of one of its subkinds, not to mention the highest-level model family. Newton's laws, therefore, were sometimes regarded as necessary truths and treated as unfalsifiable, or they were treated as definitions, because they contains a categorization, which defines the fundamental concepts such as "inertia" and "force" in Newtonian theory version.

8. Conclusion

The preceding discussion supports the following conclusion: A scientific theory version contains a taxonomic model population. The highest-level model of a theory version—traditionally regarded as a set of fundamental laws or theoretical principles—can be tested only through lower-level or complex realizable models. So there is unlikely to be any conclusive test for any scientific theory version—that is, a single test that would completely confirm or falsify it. Instead, testing through models gives us a satisfactory account of the testing histories of many scientific theory versions.

Last, I should note that one point treated in this paper may cast light on the debate between realism and constructivism. I have stressed the role of realizable models, through which theoretical principles are connected with actual phenomena. If the phenomena that correspond to such models are not found in nature, then scientists will try to "manufacture" some certain systems of objects in accordance with the "blueprints" provided by such realizable models.

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