Models as a Tool for Theory Construction: Some Strategies of Preliminary Physics

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Abstract

Theoretical models are an important tool for many aspects of scientific activity. They are used, i.a., to structure data, to apply theories or even to construct new theories. But what exactly is a model? It turns out that there is no proper definition of the term "model" that covers all these aspects. Thus, I restrict myself here to evaluate the function of models in the research process while using "model" in the loose way physicists do. To this end, I distinguish four kinds of models. These are (1) models as special theories, (2) models as a substitute for a theory, (3) toy models and (4) developmental models. I argue that models of the types (3) and (4) are considerably useful in the process of theory construction. This will be demonstrated in an extended case-study from High-Energy Physics.

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1 Introduction

The purpose of this paper is to motivate and explicate the following three theses:

Thesis 1: Physics is not some ready-made thing but a dynamic process.

Thesis 2: This dynamic process is exhibited in the continuous endeavor of theory construction.

Thesis 3: As a major tool for theory construction, scientists use models.

Prima facie **Thesis 1** sounds trivial and does not seem to need any explication. Moreover, philosophers of science such as T.S. Kuhn, I. Lakatos, L. Laudan and many others have often reminded us of this phenomenon. However, it appears that there are some consequences of this thesis that do not belong to the "common knowledge" of current philosophy of science.

Physics, like all of science, is a human activity. One important feature of this activity is the physicist's pragmatic attitude: Various approximation schemes are applied that are often not justified, possibly inconsistent approaches are used (such as renormalization) and many other procedures that – somehow – lead to what constitutes the success of physics, e.g., highly corroborated predictive theories are also employed.

Most of theoretical physics[1] is – in this sense – preliminary [3]. In order to fully understand physics from a philosophy of science point of view these features have to be taken into account. If philosophers of science do not want to leave a big field to sociologists of science, they have to study more carefully what physicists are doing at their desks and – as I. Hacking [11] might add – in their labs.

The special focus of this article is on theory construction. Many of today's "theories" are finished in a strict sense. Theories seldom satisfy all the strong criteria that philosophers of science sometimes demand [6], they describe some parts of the world satisfactorily and fail to cover others. Thus, theory construction is a good example for the process-like character of physics. This is **Thesis 2**.

For a long time, philosophers of science did not look very deeply into the actual process of theory construction. K. Popper and the Logical Empiricists

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[1] The same probably holds true for experimental practice, cf. [10, 11]. This article, however, is only concerned with theoretical physics.

claimed that the philosopher can only be concerned with what Reichenbach called the *context of justification*. The *context of discovery*, on the other hand, belongs exclusively to the realm of psychology. In recent years, a lot of work has been done to better understand what scientists do when they are inventive. Psychologists aided by computer scientists have developed programs (such as BACON and others) that simulate human thought processes during the discovery of scientific laws.[2] Philosophers, too, recently re-discovered the "logic of discovery" as a subject matter worth consideration.[3] However, there is still much work to be done on better understanding what scientists do when they are inventive.

L. Nowak, in his book *The Structure of Idealization* [19], suggested that the techniques of *idealization* and *concretization* well known in the empirical sciences also apply, for instance, in the philosophy of science.[4] In physics, one often begins with a collection of (relatively) unstructured data. Then, step by step, physicists attempt to integrate them into some more general framework. In the same way, this paper focuses primarily on a description of what scientists actually do. As a special but important example, the role that models play in the process of theory construction is investigated. In the remainder of the paper it will be shown that models are indeed a major *tool* in this process. This, in turn, validates **Thesis 3**. In some future work, my reconstruction can be improved by formalizing the procedure, maybe in terms of the structuralist framework.[5] In this respect, the present work is also *only* preliminary ...

By choosing examples from contemporary physics, especially from quantum field theory, I intend to contribute to a rather neglected sub-field of philosophy of science. I cannot expect that this work will be of much direct use to a practicing physicist. However, I hope that keeping philosophy as close to science as possible will finally result in some knowledge that proves skeptical physicists such as S. Weinberg wrong. The Noble Laureate of 1979 remarked: "The knowledge of philosophy ... helps us (only) to avoid the errors of other philosophers."[6]

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[2] An informative exposition can be found in [14].

[3] A survey of the relevant work till 1980 can be found in the two volumes [17, 18], edited by T. Nickles.

[4] I wish to thank T.A.F. Kuipers for drawing my attention to this.

[5] Some work in this direction can be found in [5].

[6] [27], p. 133.

The paper is organized as follows: In Sec. 2 I contrast two different views of models, the *Classical View* (Sec. 2.1) and the *Diachronic View* (Sec. 2.2). The *Classical View* stresses static aspects of science whereas the *Diachronic View* covers vital dynamic aspects of theory change. In Sec. 3 a case-study from High-Energy Physics illustrates what has been called a *Developmental Model.* Finally, Sec. 4 sums up the main results.

2 Two Different Views of Models

The aim of the present paper is not to exactly define what a model in physics is. The reason for this abstention is, however, not that I share T.W. Adorno's view that definitions are rational taboos.[7] As early as 1961, L. Apostel noticed that a definition proper of the term "model" was, in fact, impossible, since "model" is used with so many different meanings in science, logic and philosophy [4]. That situation has got even worse in the last thirty years.

In the language physicists use, it is already hard to distinguish between the meaning of "model" and "theory". So, for example, the "Standard Model" of the strong-electroweak interactions is certainly considered a fundamental theory.

How can we understand this almost inflationary use of the term "model" in science? One reason is that "model" reflects the fact that the construction presented by a physicist is not supposed to be the "final" answer to the problem in question: The standards a theory has to fulfill do not necessarily apply to models. In a way it is safer – if one is skeptical about the products of one's own brain – to call what comes out a model. In this sense, models are a typical example of preliminary physics.

Despite Apostel's warning, some philosophers of science such as P. Achinstein [1] and M. Bunge [7] have not stopped trying to precisely determine what a model in physics is. I want to call their conception of "model" the *Classical View of Models.* This essentially static view is briefly presented in the next section (Sec. 2.1). Thereafter, in Sec. 2.2, the opposing *Diachronic View of Models* that includes dynamic elements is presented. The distinction between static and dynamic refers here (and throughout this article) exclusively to theory construction.

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[7] [2], p. 24

2.1 The Classical View of Models

The *Classical View of Models* can be best understood as a reaction by a group of philosophers of science (mainly with a strong background in theoretical physics) to the Logical Empiricist' analysis of models (E. Nagel, R. Braithwaite).[8]

For the sake of brevity, I will restrict myself here to the relevant work of M. Bunge. P. Achinstein's elaboration follows the same line of thought.[9]

M. Bunge reconstructs a *theoretical model* (or a *special theory*) in the following way. A theoretical model consists of two components:

1. A general theory,
2. A special description of an object or system (*model object*).

The Billiard Ball Model of a gas illustrates this: In this case the general theory is Newton's mechanics, the special description contains statements about the nature of a gas, e.g., that the molecules are point-like particles moving in a chaotic way in a given box. With the so characterized Billiard Ball Model it is now possible to derive the equation of state of an *ideal* gas:

$$pV = RT$$

Here, p, V and T represent the pressure, volume, and temperature of the gas respectively, R is the gas constant. Experimentally, it is known that this equation holds especially for (very) high temperatures.

Models have many remarkable features. One of them is that they – in a way – suggest their own improvements.[10] This is often obvious where idealized assumptions facilitate the description of an object or system. By means of *concretization* (L. Nowak[11]) the model can now be "improved".[12]

In the case of the Billiard Ball Model it is clear how to make the model fit the data better and to make it, in this sense, more realistic. It is well known

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[8] Details of the Logical Empiricist's conception of models can be found in the contribution by S. Psillos (these proceedings).

[9] I have discussed this in more detail in [12].

[10] This is demonstrated, for instance, by S. Toulmin, [26], p. 37 f.

[11] Cf. [19], pp. 29; see also [15].

[12] I do not want to enter the discussion of the model-reality issue. So I choose – for the moment – the minimalist, instrumentalist interpretation: "To improve" means "getting empirically more adequate".

that molecules are *not* point-like particles. They have a finite volume V_0 and this volume affects the system's equation of state, too. A modification of the model object along these lines leads to the van der Waals equation:

$$(p + \frac{a}{V^2})(V - b) = RT$$

with adjustable parameters a and b depending on the special system under investigation.

This improved equation of state of a gas allows now, for instance, a qualitative understanding of the liquid-gas phase transition. In cases where even the van der Waals description of a gas proves insufficient, there is a systematic way in statistical mechanics to successively improve the model by calculating higher virial coefficients.

Models of this kind are used for two main reasons:[13]

1. **The testing of theories:** General theories such as Newton's mechanics[14] cannot be tested without making assumptions about some object or system.[15] Consequently, there is not much to be said about a gas from a "fundamental" point of view.

   However, there are general theories such as quantum electrodynamics (QED) that can be tested directly. Without specifying any additional model assumptions, cross sections and other physical observables can be deduced and – subsequently – confronted with the available experimental data. Now, one might argue that QED is not a general theory. Instead one has to choose general quantum field theory. Starting from this theory, QED is already a special model because for QED the "force law" has been specified. Since this issue is primarily place a matter of terminology I shall not continue discussing this point.

2. **The probing of theories:** Sometimes physicists are interested in the qualitative type of behaviour of a given theory. In this case, constructing a simple model (i.e. specifying a model object) can allow some interesting insights. This function of a model comes close to what will

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[13] Details can be found in [22].

[14] "Newton's mechanics" here means the set of three axioms, without specifying the special force law.

[15] There was a lot of confusion in the literature about auxiliary assumptions, initial conditions, model assumptions and the like, see, for instance, the "battle" between H. Putnam and K. Popper in [9].

> be described in Sec. 2.2.2 under the heading "Toy Models". Such models lack any direct physical application, they are just there ...

There is a wealth of examples for models that fit this scheme fairly well.[16] Nevertheless, this view is not a comprehensive account of models in physics. Additional and, in fact, essential aspects shall be taken into consideration in the following.

2.2 The Diachronic View of Models

The *Classical View* of models in physics is, essentially, a *static* one; it describes what kind of entity certain models are. Consequently, this scheme does not cover *dynamic* issues like theory construction.
In this section, three different types of models are discussed: *Models as a Substitute for a Theory* (Sec. 2.2.1), *Toy Models* (Sec. 2.2.2) and *Developmental Models* (Sec. 2.2.3). Let us begin with

2.2.1 Models as a Substitute for a Theory

Models as a Substitute for a Theory are of utmost importance for actual research. Quite often in physics there is a fundamental theory that should – in principle – permit the solution of a given problem. However, the theory might be too complicated to handle in practice: The required equations are either too complex to solve with the current analytical and numerical tools, or – even worse – cannot be formulated at all.
There are many examples of such a situation in science: Quantum chromodynamics (QCD), the "fundamental" theory of strong interactions, can – so far – not be used for direct studies of the structure of hadrons and nuclei.[17] Another example is almost the entire field of solid state physics. Because of the complicated correlations between many particles, physicists have to introduce simplifying "model"-assumptions. It is just impossible to reconstruct the behavior of, say, a crystal in terms of quantum electrodynamics (QED), the quantum theory of electromagnetic interaction.

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[16] Others, like the Bohr Model of the atom, do not fit that easily but have been somewhat forced to do so, cf. [1].

[17] For some years, however, physicists have been using high-powered computers for solving the relevant QCD-equations on a finite space-time lattice. This CPU-intensive procedure is still not free of conceptional difficulties, see [24].

Instead, physicists construct phenomenological models that effectively describe the relevant degrees of freedom of the system under consideration. Nucleon and pion-fields are, for instance, the relevant degrees of freedom of low-energy nuclear physics. In the course of investigating the physics of superconductors, certain electron pairs (Cooper pairs) turned out to be essential. This enormous *physical insight* represents the foundation of the BCS-theory of superconductivity, as formulated by J.Bardeen, L. Cooper and R. Schrieffer in 1957.

The technical advantage of this class of models is that they are easily (or at least: in principle) soluble. However, the relation between the model and the corresponding fundamental theory is somewhat fuzzy. Consequently, the theoretical motivation of the models is unsettled. Furthermore, *Models as a Substitute for a Theory* often entail many free parameters that have to be determined empirically.

From the above considerations one might conclude that using *Models as a Substitute for a Theory* primarily for pragmatic reasons is some exclusively negative issue. This is, in fact, not the case at all! Models often provide more physical insight than a fundamental theory, whose physical content might be too difficult to disentangle. The following example from quantum field theory illustrates this.

Due to the special structure of quantum chromodynamics (QCD), this theory is applicable (and consequently: testable) – within the standard perturbative-theoretical scheme – only within the high-energy realm. In the low-energy domain of nuclear and hadron physics there is, however, no direct way to solve the equations. In hadron[18] physics, diverse phenomenological models permit the calculation of hadronic properties, but at the price of being inexact and not fundamental.

One such model is the *MIT-Bag-Model.* According to this model hadrons consist of three massive quarks that move freely in a rigid sphere of radius R. That hard sphere guarantees that the quarks remain confined inside, a requirement of QCD.[19] The fact that the quarks are allowed to move freely inside the sphere takes another feature of QCD into account, called asymptotic freedom.

But why is there a sphere at all? Within the model the explanation is as

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[18] Hadrons are particles that are governed by strong interactions, e.g. protons, neutrons and pions.

[19] Confinement is not yet rigorously proven, but computer simulations suggest it [24].

follows: When a hadron is created, the quarks "dig a hole" in the complicated non-perturbative vacuum populated with gluons and other (scalar) entities. Thus, space is separated into two very different regions: The foreseeable *inside* (with quarks) and the messy *outside* (with gluons *etc.*).

Now, quarks moving inside the hadron expel a certain pressure on the bag's surface. That pressure has to exactly balance the pressure of the vacuum surrounding the hadron, thus guaranteeing stable hadrons. Its numerical value is determined by fixing some experimental datum.

With these model assumptions and considering the fact that free quarks inside the cavity obey – as massive fermions – the free Dirac equation, one can derive an expression for the baryon energy as a function of the radius R. After minimizing this energy in respect to the bag radius R one finally ends up with an expression for the total baryon energy.

It turns out that the resulting description of hadrons is quite good but there are a couple of shortcomings. One is that the mass of the pion is much too high. Another is that there is no mass difference between the nucleon and the delta particle. Again, it is obvious how to *concretize* the model assumptions: Additional, physically motivated energy terms can be introduced leading to a more "realistic" description of hadrons.

In summary, the main advantages of this model are that it is very easy to handle (it is almost possible to solve it analytically) and that it allows new insights into the consequences of important features of the underlying "fundamental" theory QCD.

So, *Models as a Substitute for a Theory* do not only serve to make actual calculations feasible but, furthermore, allow some insight into physical mechanisms ("How does the confinement mechanism work?") that cannot be directly studied with the "fundamental" theory (in our example QCD).

2.2.2 Toy Models

Toy Models, as I understand them here, are models without any direct intended physical application. Since physics has to do with a description of observations in terms of suitable theories, one might ask why *Toy Models* are studied at all. It is, indeed, very common in modern physics to investigate types belonging to this class of models. Examples are known from all branches of theoretical physics.

For the sake of illustration, let us first examine an example from quantum field theory. Quantum field theory is the general theory of quantized fields.[20] It provides the frame for a description of the interaction of quantized fields and gives concrete prescriptions for how to calculate – in principle – measurable quantities. In the common formulation one starts with a Lagrangian density that determines the nature of the particles involved as well as their mutual interaction. Special examples of a quantum field theory are the above-mentioned theories: quantum electrodynamics (QED) and quantum chromodynamics (QCD).

The φ^4-theory is characterized by the following Lagrangian density:

$$\mathcal{L} = \frac{1}{2}\partial_\mu \varphi \partial^\mu \varphi - \mu^2 \varphi^2 - \lambda \varphi^4$$

Here, φ represents a self-interacting scalar (= spin-0). The parameters μ and λ characterize the "potential". Although the model is well formulated there is no such (independent) scalar particle in nature.

Why is this theory proposed at all, then? Obviously, it is possible to construct such a theory for the general formalism of quantum field theory that does not specify both the concrete nature of the fields involved *and* their mutual interaction. Quantum field theory only provides the framework for restricting the fields to obey certain general constraints.

It is worth noting that the φ^4-theory is the simplest quantum field theory one can imagine. This, in turn, makes it possible to learn a lot from studying this theory carefully. To mention only a few points:

1. To get a "feeling" for what quantum field theories really are.
2. To get used to special formal techniques (e.g. renormalization).
3. To extract general features which possibly every quantum field theories has.
4. To providing a tool-box for possible mechanisms that can be "plugged-in" to a future theory.

The φ^4-theory exhibits the feature of spontaneous symmetry breaking. This phenomenon occurs for certain parameter constellations. In this case the state of lowest energy (the "ground state") does not respect the symmetry of the original Lagrangian density. That symmetry is said to be broken.

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[20] An introduction "for philosophers" can be found in [23].

This mechanism proved to be the "missing link" in the construction of the Weinberg-Salam theory of electro-weak interactions. In order to formulate this theory in the language of gauge theories, the intermediate bosons had to be massless. However, from weak-interaction phenomenology it was well known that the intermediate vector-bosons (the mediators of the weak force) had to be very massive. So a φ^4-like mechanism for a spontaneous symmetry breaking was included, generating the dynamical mass of the vector-bosons.

2.2.3 Developmental Models

Besides this more or less pragmatic function, models are frequently used in the process of developing a "fundamental" theory. *Developmental Models* represent – in a systematic *and* historical respect – a step towards a "ready" theory. The term *Developmental Model* was first introduced by J. Leplin [16] in 1980. Leplin pointed out which role models played in the context of the development of the early quantum mechanics by M. Planck and A. Einstein. But, *Developmental Models* were not only valuable in the Good Old Days. They are, in fact, an indispensable tool for theory construction in contemporary physics. An important contribution to the reconstruction of the development of scientific theories was made by P. Suppes. In 1962, Suppes reconstructed the development of a psychological theory (a special stimulus-response theory) in terms of an increasing "tower" of models [25]. "Increasing" here means that a model that is "higher" in the hierarchy is compatible with more general laws. Furthermore, such models also usually cover a larger set of phenomena than "lower" ones.

3 Case-Study: From the Hadron Zoo to Quantum Chromodynamics

The following case-study[21] is taken from High-Energy Physics. Quantum chromodynamics (QCD) is, as has already been mentioned, now almost generally accepted as the "fundamental" theory of strong interactions. It is supposed to cover many phenomena from nuclear and particle physics.
How did physicists arrive at this theory? The aim of this section is to reconstruct the *historical* formulation process of QCD by means of a hierarchy of

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[21] Historical details can be found in Refs. [20, 21].

consecutive *Developmental Models.*

1. Collection of Data: *The Hadron Zoo*

   The first phase of theory construction usually starts with collecting the data that the theory is supposed to describe. Sometimes these data have been known for a very long time and have already been framed by some theory or model. Further, it is possible that physicists discover data "by accident", like in the case of the $3K$ background radiation in 1963 by A. Penzias and R. Wilson or, more recently, high-T_c superconductivity by J. G. Bednorz and K. A. Müller.

   In the first stage of the physics of strong interactions (starting in the early 1930's) experimental physicists collected a tremendous amount of data of new and so far not yet classified "elementary particles". These particles were initially produced in low-energy nuclear reactions occurring when an accelerated atomic nucleus hits some metal foil (consisting, inter alia, of a large number of atomic nuclei). In this case the nuclei of the foil happen to "react" with the nuclei of the accelerated beam. As a result, new particles are produced. Experimentalists determined the mass and electrical charge of these particles. If the particles were unstable they tried to extract the properties of the decayed particles from the corresponding decay products.

   It should be noted that the – so far – unknown theory (*i.e.* QCD) was not assumed for the determination of particle properties. The identification of mass, charge and decay products of the new particles only presupposes an older, highly confirmed and accepted theory: Maxwell's theory of electromagnetism.

2. Introduction of New, Internal Concepts: *Spin, Isospin and Strangeness*

   For a theoretical physicist not much is achieved with a listing of many positive data. He wishes to understand *why* the data are as they are or, as some philosopher might even ask, how the data must be. For this purpose, it is necessary to introduce concepts that structure the given data. In this sub-section we are mainly concerned with "internal" concepts, i.e. concepts that refer only to the data without assuming any high-level laws. But how exactly do scientists proceed to achieve this aim? The following methodological rules, extracted from an analysis of the research process, might help:

(a) Analyze data in respect to similarities. Is it possible to arrange some data into “blocks”?

(b) Adopt old concepts that proved useful in a similar situation.

(c) Construct new concepts analogous to already known ones.

Common to all these rules is the postulation of some *analogy relation* between different parts of a “data field” or between some already comprehended and *still* not comprehended structures.

Again, this will be illustrated with the example of the physics of strong interactions. The process of gaining a deeper understanding of elementary particles starts from a thorough analysis of the corresponding decay channels. Some particle might “prefer” to decay exclusively into one channel while other channels happen to be “forbidden”.[22]

The first concept to be introduced was *spin.* Spin is an angular momentum-like quantum number whose *invention* (for electrons) was originally motivated by the famous Stern-Gerlach experiment: When a beam of atoms with an uneven number of electrons encounters an inhomogeneous magnetic field, it splits into two partial beams. One can proceed in just the same way with protons and other *stable* particles.[23]

Nevertheless, this procedure cannot be applied to unstable particles. Since most known particles are in fact unstable, additional theoretical arguments are necessary. To mention just a few:

(a) **The Conservation Law for the Total Angular Momentum** (= orbital angular momentum + spin): Starting from particles whose spin is already known (or conventionally fixed), the spin of new particles can be determined by analyzing decay products of suitable reactions.

(b) **The Principle of Detailed Balance:** It is known that the transition matrix element for the reactions $A + B \rightarrow C + D$ and $C + D \rightarrow A + B$ are equal. Thus, the ratio of the corresponding cross sections is only a function of the respective angular momenta. This implies that unknown spins can be related to already known ones.

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[22] One more example of the anthropomorphic language of physicists that I adopt here.

[23] The particles have to be at least quasi-stable, i.e. they should not decay within the apparatus.

(c) **The Spin Statistics Theorem:** According to this theorem (W. Pauli and G. Lüders, 1954) particles have either integer (bosons) or half-integer (fermions) spin. This principle theoretically establishes that unstable particles also have the intrinsic property "spin".

Whereas the spin concept has been transferred from atomic physics to elementary particle physics, "isospin" and "strangeness" appeared for the first time in particle physics. In order to fully understand why certain decay processes occur and others do not, it is indeed necessary to introduce additional conserved quantities. In 1932 W. Heisenberg postulated that "isospin" is a conserved quantity in strong interactions.[24] Already the term "isospin" exhibits the *structural analogy* and *conceptual isomorphy* to the spin concept. Heisenberg recognized that protons and neutrons are very similar in many respects. Although they differ in their (electrical) charge, Heisenberg postulated that strong interactions are "blind" in respect to the particles' electric charge.

After World War II it was possible to accelerate particles to higher and higher energies. It then became apparent that more and more particles did not fit in the scheme. Prompted by those experiments, M. Gell-Mann and others introduced "strangeness" as an additional quantum number in strong interactions in 1953.

So the hadron "zoo" became gradually organized. Furthermore, physicists began to develop some intuition concerning possible and impossible particle reactions.

This example shows paradigmatically how science proceeds from the known to the still unknown. New concepts (like spin and isospin) are derived from analogical reasoning and lead by experimental discoveries.

3. Refining and Unifying Internal Concepts: *The Eightfold Way*

An essential feature of the process of improving the data-modeling is the "enrichment" with general principles and the integration of preliminary concepts into already known fundamental ones, whereby the intention is to achieve the desired unified description.

In the case of hadron physics, it became, after a while, obvious to the physics community that the classification scheme in terms of "spin",

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[24] Heisenberg himself used the term "Isobarenspin".

"isospin" and "strangeness" was not the last word. After all, there was no general dynamic theory that covered creation and annihilation processes of elementary particles. There were only models that were tried by physicists (and, possibly, intended to be part of a *Developmental Model* hierarchy) but led nowhere. An example of this sort of model is the Yukawa theory for mesons. The major desideratum was a field theory for hadrons comparable in its extent to the quantum electrodynamics (QED) for electrons. Although QED was not without conceptional problems, it was nevertheless considered a very successful dynamic theory for all phenomena governed by electromagnetism only. However, the "connections" that physicists tried to establish between special features of strong interactions and QED were often misleading.

Instead, M. Gell-Mann and G. Zweig worked out, independently of each other,[25] a unifying classification scheme in terms of spin, isospin and strangeness quantum numbers. Driven by the observation that eight and ten of the hadrons of lowest energy have a mass in the same range, these authors postulated that they have in fact the same mass. This is a typical *idealization.*

Mathematically, the feature of a common mass can be expressed in terms of a new symmetry. This symmetry is called $SU(3)$ or – as Gell-Mann dubbed it– "The Eightfold Way". All strongly interacting particles belong to "multiplets" or – in suitable group theoretical language – irreducible representations of the group $SU(3)$. Famous examples of such multiplets are the meson- and baryon octet and the baryon decuplet.

Within the group theoretical framework it turned out that the octet and decuplet representations can simply be constructed by tensor products of the "fundamental" representation of $SU(3)$ that is itself – interestingly enough – not realized in nature.

For the tensor products of three fundamental representations 3 (triplet) one obtains:

$$3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$$

Thus, one decuplet (10), two octets (8) and one singlet (1) can be "generated". All but the singlet have a counterpart in the real world.

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[25] Differences between the two approaches are pointed out in [21], pp. 85.

Similarly, for the product of a triplet (3) and an anti-triplet ($\bar{3}$) one obtains:

$$3 \otimes \bar{3} = 1 \oplus 8$$

Besides the (physically realized) octet, again one "dubious" singlet occurs.

What is the status of the fundamental representation 3? Although there is no obvious counterpart in nature, hadrons seem to "consist" of entities "belonging" to it. Why is the fundamental representation not realized?

In the mid-sixties, many physicists were rather skeptical of a possible ontological interpretation of the elements of the fundamental representation later to be named "quarks" by M. Gell-Mann.

But there was still another problem if quarks turned out to be really there. Being spin-1/2 particles and thus fermions, quarks should obey the Pauli-Principle. However, in the case of the baryon decuplet it can be easily shown that just this fundamental principle seems to be violated if quarks were more than just a quirk of group theory.

This example shows how new perspectives result from unifying old concepts. The resulting description of data is now more comprehensive.

4. (Ad hoc) Correction of (External) Inconsistencies: *The Color-Concept*

   A forerunner of a theory might be inconsistent. Usually, one distinguishes between *internal* and *external* inconsistencies.

   A set M of sentences is **internally inconsistent**, if M permits the derivation of some statement A and its opposite $\bar{A}$. Clearly, a physical theory has to be internally consistent.

   A theory is **externally inconsistent**, if a contradiction ensues when additional external principles such as conservation laws are taken into account. In this sense, the quark model (as described above) is inconsistent. In order to understand how this contradiction was resolved, let us follow the historical development.

   The fourth stage in the construction of quantum chromodynamics started with some famous experiments. Experimentalists at Stanford studied the scattering of high-energy electrons on protons. They clearly demonstrated that the nucleon itself is not point-like, but displays an inner structure just like the atomic nucleus.

In his famous Parton Model R. Feynman could subsequently explain the new data by assuming that the nucleon "consists" of three particles of spin 1/2. It was only a straight forward step to identify these particles with Gell-Mann's quarks.

To finally succeed in this identification it is important to eliminate the contradiction with the universally valid Pauli Principle. M. Gell-Mann dealt with this problem in the simplest way imaginable: He postulated the existence of a new quantum number, called *color*, that re-established the validity of the Pauli Principle for quarks.

It should be noted that the introduction of "color" was nothing but an *ad hoc* hypothesis in the first stage. Shortly thereafter this ingenious move turned out to be the final step towards a gauge theory of strong interactions.

The example given above is one more piece of evidence for I. Lakatos' famous statement that "it may be rational to put the inconsistency into some temporary, *ad hoc* quarantine, and carry on with the positive heuristics of the programme."[26] Strictly speaking, only the one true theory has to be fully consistent. However, this theory might not even exist.

5. Integrating Everything into a General Frame: *The Gauge Theory Concept*

Depending on the complexity of the data to be described several of the steps discussed above might turn out to be necessary. The "ultimate" aim of physicists is, however, to embed everything in a general framework.

In the case of elementary particle physics, quantum field theory is such a generalized framework. Quantum field theory provides a general formalism that facilitates the description of the interaction of "elementary" quantum fields. Historically, this structure resembles what I. Lakatos called the "hard core" of a scientific research programme.[27]

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[26] [13], p. 58.

[27] J. Cushing [8] argued convincingly for this thesis.

> Since the early 1950's, QED is – mainly because of its great empirical success – *the* paradigm of a quantum field theory. Calculations of physical observables like the anomalous magnetic moment of the electron agree with the experimental value by up to *twelve* significant figures. After the establishment of QED, physicists soon extended the formalism and started to quantize other fields. A special sub-class of all possible quantum field theories is of considerable significance: renormalizable local gauge theories.
>
> Following in the spirit of these theories, firstly the theory of electroweak interactions and, some years later, QCD were developed. It is worth noting that the color-concept played a key role in this process.

This is – so far – the end point of the development of the physics of strong interactions. There is diverse research in progress to include QCD in an even more comprehensive theoretical framework. However, this kind of physics is not yet well enough established for our purposes.
This – somewhat lengthy – case-study should show in detail the role played by models in the process of constructing a new theory.

4 Summary

Physicists use many different types of models. The *Classical View* covers pragmatic aspects such as applying, testing and probing of already existing theories. Within the *Diachronic View*, dynamic aspects of science can be considered. Models play a major role in the process of theory construction and provide possible physical mechanisms in advance that can subsequently turn out to be fruitful. All in all, models are a favorite tool of preliminary physics.

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