THE ROLE OF EXPERIMENTALITY IN CONCEPT FORMATION IN PHYSICS: QUANTIFYING EXPERIMENTS AND INVARIANCES

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ABSTRACT

The role of experimentality in concept formation in learning physics is discussed and it is pointed out how the meaning of every physical concept is inherently tied to empirical ways to determine it. This means that in order to get a proper understanding of the concepts of physics, the concepts can not be introduced starting from their role in pre-existing theoretical structures, instead, they must be motivated through the experimentality in a way which is meaningful for the student. In this presentation, the rationale behind this point of view is discussed starting from ideas of the nature of concept formation in physics, and of the structure of knowledge in physics. The leading idea is that construction of knowledge is similar in the research and learning of physics. It is discussed how the meaning of every concept of physics is created through the so-called quantifying experiments and how the definition of every quantity is tied to invariances recognised in these quantifying experiments. This process is in the core of the concept formation and structurisation of the knowledge and it should be reflected on physics teaching as well. How this happens, and to what extent it is possible is discussed. Detailed examples of the practical teaching procedures based on the ideas presented here are given in another contribution. The presentation closes with outline of the guidelines for structured physics teaching where the role of experimentality in concept formation is taken into account.

1. INTRODUCTION

Physics is an experimental science. By this remark it is frequently meant that physical theories must be verified by experiments. Theories or models, which do not match with observations and experiments, should be rejected. However, deeper understanding on the role of empirical exploration is gained by noting how it has an essential role in the whole process of concept formation in physics. The process begins from perception and observation, and the concepts acquire more definite meaning by controlled experiments and measurements. How this happens, is the main topic of the present contribution. From the point of view of teaching, this means that concepts can not be introduced starting from their role in pre-existing theoretical structures, instead, they must be motivated through experimentality, which is meaningful for the student. In the following experimentality refers to all the meaningful ways of obtaining qualitative or quantitative information.

If experimentality is in the core of concept formation in physics, why should it not be in the core of learning physics? The reason for this connection is the view, that the processual character of the learning and doing physics are similar enough to warrant the attempt to seek guidance for teaching from the process of scientific inquiry in physics. Similar idea is also behind the Novak’s views of the similarities between learning and scientific inquiry in general [1]. Science and learning can be seen as different levels or phases of the same process, which are similar or at least parallel processes for creating knowledge. Therefore, the central theme also in teaching physics is the process of concept formation and the role of experimentality in it.

The ideas of the essential role of experimentality in physics teaching have been the backbone of teacher’s education in the University of Helsinki for nearly two decades. Views discussed in this contribution are essentially based on a background philosophy of teaching physics created by Kaarle and Riitta Kurki-Suonio, and disseminated since 1980's in lectures for in- and pre-service teachers and in publications in Finnish [2]. It has provided a general background philosophy for orientation and giving guidance in selection of particular instructional methods. However, here we do not wish to introduce a complete theoretical framework, instead, the present contribution introduces only some of the key ideas of the role of experimentality in concept formation in physics and its implications on teaching physics. Practical examples of the ways these ideas can be utilised in designing teaching procedures are given in a contribution by Hämäläinen in this conference [3, 4].

2. EXPERIMENTALITY IN CONCEPT FORMATION

Concept formation has a central role in all attempts to describe physics as a scientific theory and its structure. It is essential to know how physical concepts acquire their meaning and what are the roles of experimentality and theory in this process.

The conception of meaning adequate for scientific theories can not be separated from actual scientific practices concerning meaning [5], i.e. from the scientific process itself. Every physical concept has its origins in sensory-perception and it has gone through a certain evolution process. Meaning of a scientific concept can be seen as "*a two-dimensional array which is constructed on the basis of its descriptive/explanatory function as its develops over time*", and this array is called a "meaning schema" [5,6]. The meaning schema is open to development and it carries also all the subsequent changes with it. The concept of meaning schema has turned out be useful in description of conceptualisation process as encountered in physics history [5] and is also used in description of learning process of physics [6]. Here the conception of meaning schema is also adopted, but in a slightly more restricted sense describing the formation of patterns with assigned meaning in the qualitative level. In the quantitative level, term concept is used as a quantitative counterpart of meaning schema.

The formation of the meaning schema starts from the sensory perception, it takes place in interplay between experimentality and theory, and it is directed from phenomena to theory. All physical concepts, terms, quantities, laws and theories are therefore based on empirical-theoretical meaning schema, always open to further development. Meaning schema is continuously evolving and through its development it acquires more precise meaning, finally becoming a physical concept. The concept, therefore, represent something that has already been understood. We can say that the meanings are created first. Arons expresses similar ideas of the importance of creating the meanings first [7].

The way the process of concept formation is directed from phenomena to theory is represented schematically by a diagram in Fig. 1. The concept formation takes place in a cycle, which consists of *representation and interpretation*. Representation proceeding from Nature towards theory is guided by seeking of structures through generalisations, which are justified by using inductive reasoning. Interpretation means understanding existing reality starting from the principles at the conceptual level, in the level of theory. Predictions concerning specific situations are inferred from general principles by using hypothetico-deductive reasoning.

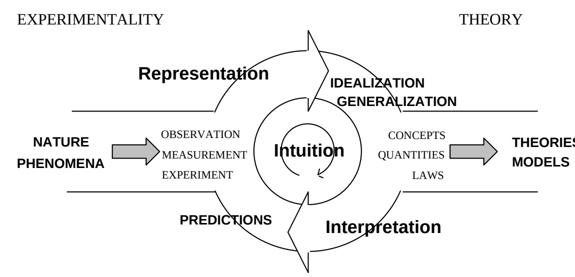

Fig.1. Cycle of concept formation. The process is directed from phenomena to theory.

The notion that concept formation, as presented in Fig. 1, is not only directed from phenomena to theory but that it actually takes the form of a cyclic process, means that the every physical concept is intimately associated with a process, where experimentality and theory are joined together. *Concepts are inseparably connected to the scientific process, which creates their meaning*.

Concept formation is never tied to logical necessity, instead, an intuitive component is always a part of it. The scientific process, including learning, can therefore be regarded rather an intuitive than a logical process, although the logic has a central role in this process. The meaning schemata and their relations are grasped through intuition. Intuition not only guides concept formation, but by intuition, one thinks that every phenomenon is ruled by laws. In experiments or observations one finds stronger or weaker correlations between results of related measurements. By intuition the correlations can be interpreted as evidence of dependencies, the relations between the concepts of theory. However, structurization necessarily requires logic and the further the abstraction level of the process rises the more central role logic has in governing and controlling the process.

3. PHYSICAL CONCEPTS, QUANTIFYING EXPERIMENTS AND INVARIANCES

The problems of teaching physics are very much identified with the problems of creation of physical concepts and defining physical quantities. Thus the phases which can be distinguished in concept formation and in defining a quantity are also present in learning and in teaching. This means that certain advantage is gained if instruction follows this natural course of development. Instruction should start from the qualitative level (perception), then advance through the quantitative levels of quantities and laws (quantification), finally entering the level of structured theory and explaining models (structurisation). This series of processes in teaching *perception – quantification – structurisation* is represented schematically in Fig. 2. In the diagram the symbol between the levels describes the concept formation process as discussed previously and shown in Fig. 1.

Perception: As already noted, concept formation starts from the level of qualitative information, *by perception*, and builds up basic meaning schema and schemata by recognition and classification of phenomena and their relationships. In this process the *meaning is created first* through experimentality in form of sensory experiences, observation and qualitative experiments. A *class of meaning schemata* is thus formed, which include not only entities (objects), but also phenomena and their properties (qualities).

All these meaning schemata *carry the possibility to become conceptualised*, which means that the concept is

introduced as an abstract equivalent of the meaning schema.

Quantification, which creates a quantity from a property (quality), is the essence of physics, and it can be seen as central process in creating knowledge in physics. Quantification is based on experiments, which verify the defining law of the quantity, and also tell how the quantity can be measured. It is also the first big fundamental abstraction in concept formation. In the qualitative level quantification is preceded by prequantification which means comparison of the degrees of the properties of entities and phenomena. Quantification leads to formation of quantities, which are *quantitative representations* for properties. In this process quantities also acquire numerical values and units.

The mutual dependency of the properties become represented as relations between quantities, and these representations are *laws.* Therefore, the definition of every quantity is tied on laws, and even more, on the process where the very laws and quantities are created. The defining law is always a conservation law, i.e. a well-defined invariance between some factors that affect the phenomenon. Invariances may exist in different forms, but every defining law can be expressed as invariance. Therefore, *quantities are essentially invariants*.

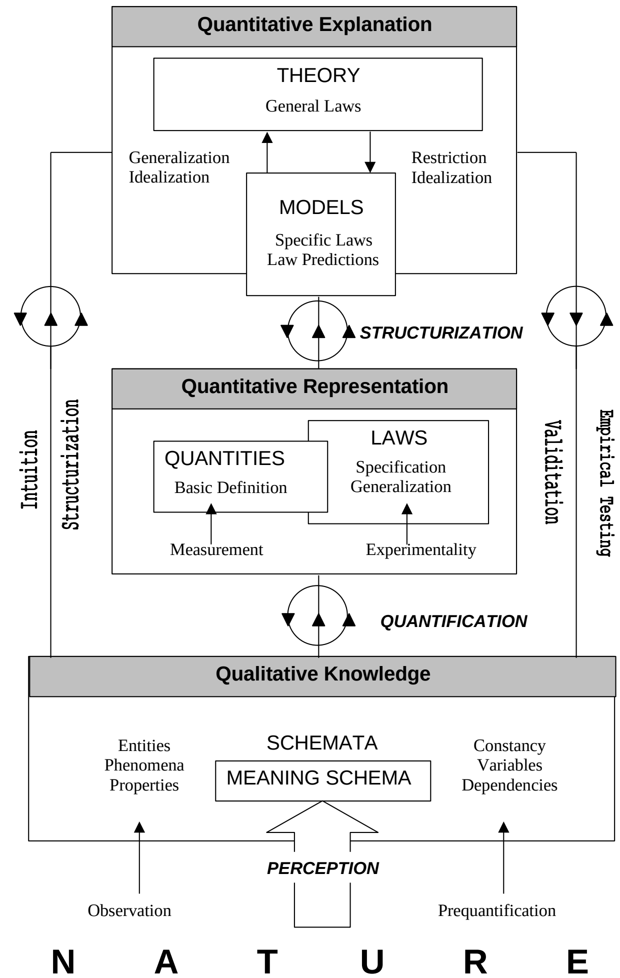

Fig. 2. Structure of physics and the hierarchical levels of the concept formation, leading to quantities and laws, in physics. The sequence of concept formation starts always from perception.

The notion that quantities are invariants means that attention has to be paid to the ways the invariances are demonstrated clearly, e.g. by means of graphical representations. In this way the experimentality, by connecting the concepts to invariances, takes the central role in forming the meaning of concepts. It becomes clear, that concept formation can not start from theory and experimentality reduced to testing of the concepts. Instead, it starts from phenomena and proceeds toward formation of theory.

Quantification creates a hierarchical network of quantities, in which every quantity is linked to other quantities in many different ways. *A rigid hierarchy* prevails in the network of quantities. The quantitative relations, the laws, between quantities rule this hierarchy. It does not allow much freedom in the order in which the quantities are introduced, if one wishes to retain the logical ordering of the process, and thus the correct meaning of the quantities tied on these processes. On the qualitative level the hierarchical structure of physics is much less rigid. Relations between objects' qualities are more vague, and this kind of *soft hierarchy* leaves more freedom to the introduction of topics.

Some examples of the quantification and its role in teaching according to above outlined principles will be given in the contribution by Hämäläinen et al [4].

<u>Structurisation.</u> The process that leads into the highest level of the conceptual structure of physics may be called logical structurisation, which is already present in the qualitative level of knowledge. A theory, although always open to development, is to a certain degree adequately completed logical structure, which is composed of the structural paradigms and general laws, which are the rules of the theory. Theory is always in a state of further development, because it acts as a basis of explanation and is through it constantly weighed against observations. Any inconsistencies rapidly lead to modifications and changes in the structure of the theory or in the meaning of the concepts. This openness of structures to change is readily associated with development and self-correction capability of physics.

Modelling has a central role in explanation process and in learning, how concepts are used in explaining [8]. By models we mean restricted explanatory, mathematically formulated structures which are obtained by limiting the range of validity of the theory. Models always correspond to the real phenomena in different conditions, and can therefore be experimentally tested, contrary to theory itself, which is beyond direct experimental testing. Because of this *modelling capability*, the theory becomes the basis for the explanation, and also a basis for understanding of various phenomena [8]. It can be claimed that theory is the basis of understanding through its capability to explain through modelling. Empiry in this level is experimental research to verify or falsify the models, i.e. select the correct models, and through this selection, verify the predictions of the theory or give insight, how the knowledge structure needs to be corrected or augmented.

4. DIRECTIONS OF LEARNING AND TEACHING

As we pointed out earlier concepts are processes. From this notion it naturally follows that the fundamental goals of physics education concern processual aspects of learning. For a student, learning physics is conceptualisation. Therefore learning physics has the same natural direction as the concept formation has, from perceptions to conceptions, and from experiments to theory. Teaching should obey the direction and phases of concept formation as expressed in Fig 1 and Fig. 2.

The hierarchical levels of concept formation (see Fig. 2) represent different abstraction levels, which set gradually increasing demands for a student's ability in formal thinking. Therefore, they provide suitable starting points for setting target levels according to a pupil's talents, when physics curricula are designed for different grades. Simultaneously, for the teacher they provide a means for a substantially lighter syllabus and limiting the study of each topic to a suitable level. The teacher should recognise that proceeding to higher levels can be done later, and that all levels are anyhow intermediate goals in a continuous process.

The level of qualitative knowledge is the most important of the hierarchical levels, because upper levels can be reached only through it. This level lays the foundation of the scientific use of language. Qualitative experiments play a significant role at this level, which is the key to understanding. Instruction should always start from this qualitative level, paying attention to observation, classification and description.

Quantification builds a bridge from the qualitative level to *the level of quantities and laws*. At this level as well, demonstrations and laboratory exercises have paramount importance. One meets the rigid hierarchy of concepts that dictates the order in which the concepts can be introduced. The natural direction of the process leads from experimental measurements through numerical and graphical presentation of the pertinent invariances to the algebraical presentation. Graphical presentation is an important phase of concept formation. It is an abstract presentation of results of concrete experiments, from which it is possible to proceed to higher abstraction levels of algebraical representation.

The level of theories is the uppermost target level. The conceptual level of the students is the crucial factor that dictates in which topics this level is possible to reach. However, the theory is the outcome of process starting from perception. Instruction emphasising the role of experimentality in concept formation can not start from the theory. Of course, during the later stages of instruction e.g. modelling and testing model predictions have important role as a part of teaching.

To use experimentality so that it truly supports learning and concept formation experimentation must proceed the introduction of concepts. This we call *perceptional experimentality* [3,4]. Practical ways of instructions based on perceptional experimentality are discussed in the contribution by Hämäläinen [4].

Still, experimentality in teaching can not be equal to the true experimentality of science, where everything must be verified by experiments. There are parts of a curriculum, especially in modern physics, where the fundamental experiments can not be performed in schools. One must then rely on *narrated experimentality,* which includes all means of describing real experiments without actually performing them.

5. SUMMARY

The approach on teaching outlined here can not be formulated as a list or rules for teaching, because creative conceptualisation does not acquiesce in rules. At best, this means that in teaching the only rule is to try to, first and foremost, obey the guidelines of concept formation process, where empirical exploration has been placed on the centre of the process. The teacher may only lead the way. The building of the concepts of physics can be understood as the extension of natural perception, and the scientific method as the extension of natural thinking and the role of the teacher is to guide this development.

The meaning of every physical concept is fundamentally based on the experimental ways to determine it. In order to build up proper meanings of physical concepts we can not introduce the concepts as products of pre-existing theory. Concepts are formed as invariances found in experiments, and this principle should also be reflected in teaching practices.

In the level of theory of knowledge the presentation given is far from unified and systematic. Nevertheless the ideas which emphasise the role of experimentality in concept formation offer a comprehensive and unifying framework for development of teaching physics.

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