The characteristics of the experimental and the theoretical approach in the teaching of physics[1]

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A hierarchical level scheme is presented to describe the conceptual structure of physics. The primary role of intuitive Gestalt perception processes determines the general direction of concept formation from observation to concepts, from the concrete to the abstract and from the simple to the structural. This defines also the natural experimental approach of teaching, proceeding stepwise from phenomena through quantities and laws to theory in accordance with the scheme. Some steps of wrong-way reasoning typical of the opposite, theoretical approach found in textbooks are described and classified by means of the scheme. The scheme has been used on a teacher education course as the basis for several kinds of discussions and exercises involving studies of approach and planning of teaching events and procedures. Strong binding of present physics teaching to the theoretical approach is noted.

1. The hierarchical levels of concepts

Physical concept formation is basically a Gestalt-perception process. It involves recognition and naming of observable features (Gestalts) in the surrounding nature. The whole present cognitive structure of physics is based on a unification development, the essence of which is the recognition of ever wider structural Gestalts and, thus, the creation of unifying concepts of ever increasing generality and degree of abstraction. In very broad outline four hierarchical conceptual levels can be distinguished and given the following simple titles: 1. phenomena, 2. quantities, 3. laws and 4. theories (Fig. 1, cf. also Kurki-Suonio *et al.* 1985, 10):

[1] In J. Laurén (ed.) Science education research in Finland. Yearbook 1987–1988. University of Jyväskylä. Institute for Educational Research. Publication series B. Theory into Practice **36**, 13–26.

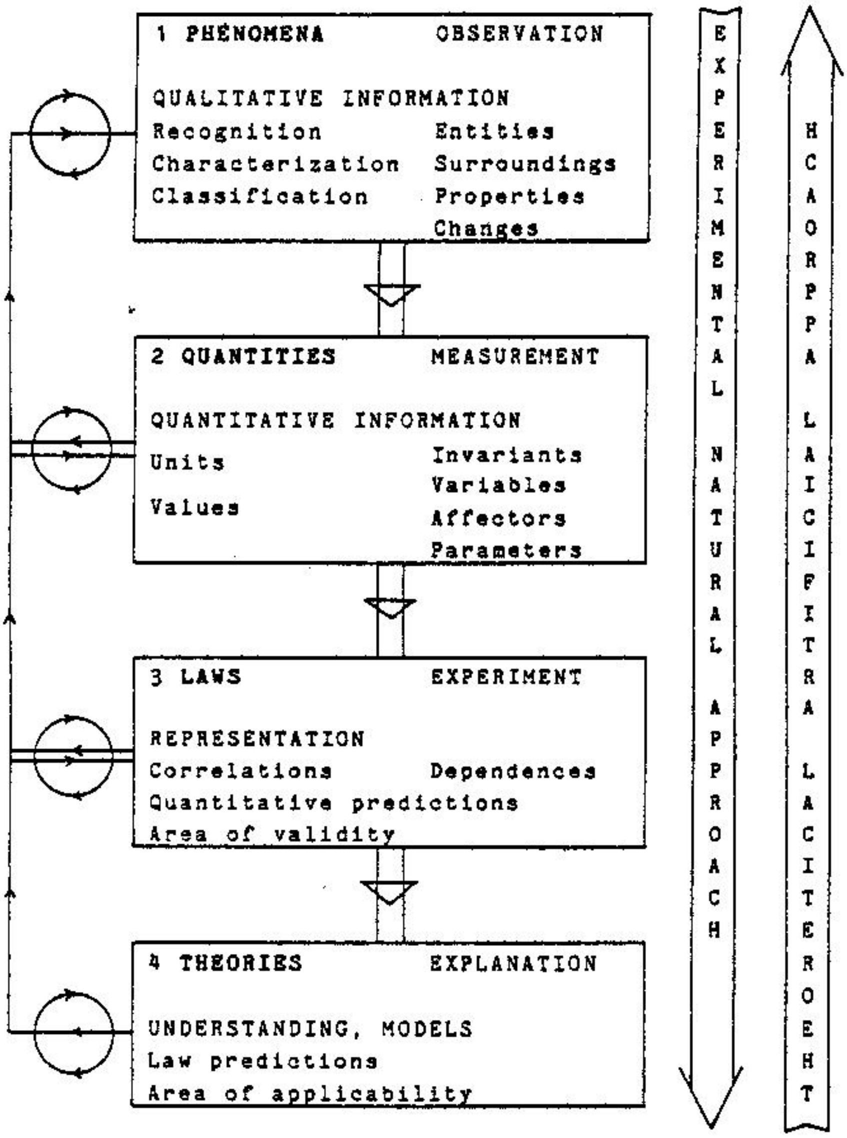

FIGURE 1. Hierarchical levels of concepts

(1) The first level of *phenomena* is the level of *observation* and *qualitative information*. On this level, the phenomena and the objects or systems involved and their surroundings are *identified*, *characterized* and *classified*. The properties which are changing in the phenomenon, those remaining unchanged, and those influencing the phenomenon are noted and observed. This is the first stage of natural concept formation, where the objects, phenomena and their properties are named. Here the phenomena are also *reduced* into simple basic types, the study of which enables one to proceed to higher levels.

(2) The second level of *quantities* is the level of *measurement* and *quantitative information*. On this level the measurable quantities are introduced which correspond to the observable properties essential in the phenomenon. They make it possible to obtain quantitative experimental information on the phenomenon, on the system and on its surroundings.

(3) The third level of *laws* is the level of *accurate representation* of the phenomenon and of *systematic quantitative knowledge*. On this level, *correlations* between the different kinds of quantities are studied with the aid of carefully designed *experiments* and interpreted as their *interdependences*. This yields experimental laws which represent the phenomenon and can be used as its simple mathematical models. These laws enable quantitative *predictions* concerning the studied phenomenon in similar or related circumstances. By testing experimentally the predictions, the areas of validity of the laws can be found.

(4) The fourth level of *theory* is the highest hierarchical level of the cognitive structure, existing only in physics. It is the level of *quantitative understanding* and *explanation* of the phenomena. A theory is defined in terms of a general basic model of the system and the basic laws, which are the operational rules of the model. By restricting the basic model appropriately it is possible to work out specific models for different real phenomena and systems in different circumstances within the area of the applicability of the theory. The basic laws then yield *law predictions* for the system studied. It is through this *modelling capacity* that the theory provides the basis for understanding different experimental laws.

Once it is realized that concept formation is basically a perception-like Gestalt recognition process, the cognitive structure of physics obtains a general direction from observation to concepts and from concepts to more general concepts, from the concrete to the abstract and from the simple to the structural. This direction is obvious when proceeding from one level to the next, from the phenomena through quantities and laws to the theory. Concept formation on a higher level is based on the lower level. It involves recognition of higher-order structural patterns of the lower-level concepts. The direction is, however, similarly present in all processes within each single level.

In spite of its general direction, concept formation is not a linear process, it does not proceed linearly from one level to the next. It is rather a cyclic, or actually a multiple spiral process. The higher-level concepts are structures of the lower-level concepts. Therefore they open up possibilities for proceeding further on the lower level and thus for building a further foundation for the higher-level concept formation. The whole level structure is thus projected into each individual level, providing them with their own internal hierarchical structures.

Phenomena are classified and new ones are identified through the laws and the theory. Many phenomena studied in physics have become possible to perceive only through the developing theoretical knowledge. The quantities and the laws constitute their own hierarchical systems from the specific quantities and laws to the general ones, from the simple to the structural ones (cf. Andersson *et al.* 1989). A similar hierarchy can be seen in the development stages of the theories and in the way the modern theories are built on the foundation formed by the classical theories. This gives physics its faculty to explain phenomena in varying degrees or depths.

Afterwards, the concept formation can, to some extent, be analyzed in terms of logical chains. Then, its cyclic structure appears to form induction-deduction loops characteristic of logical reasoning, in a way presented schematically by Figure 2 (cf. Kurki-Suonio *et al.* 1982, 15). Both in the detailed internal processes of each level and in the interactive processes between the levels one can distinguish induction steps in the form of generalizations of experimental results into theoretical conclusions, and deduction steps in the form of specific theoretical conclusions or predictions which can be submitted to an experimental test.

The formation of physical concepts, whether it involves recognition of phenomena, definition of quantities, invention of laws or development of theory, is, however, at no stage, logical reasoning but intuitive Gestalt perception. It is based on the same special pattern-recognition faculty of the brain as any formation of coherent observations from impulses received by the senses and the creation of mental pictures which can be given names. Basically it is idealization: reduction, recognition of essentials and elimination of noise. There is no logical necessity involved.

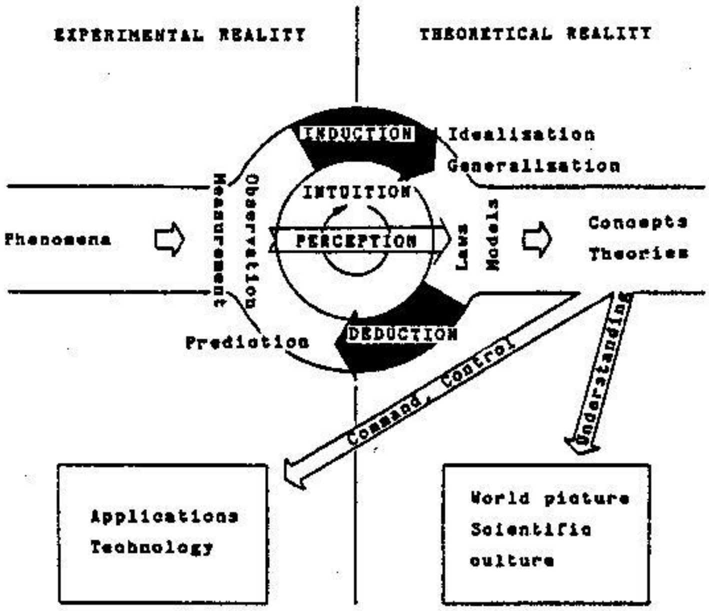

FIGURE 2. Scheme of logical processes

2. The experimental approach

Physics is a language for speaking about natural phenomena. The learning of physics is the pupil's concept formation. Teaching physics is pointing out those Gestalts, which the genii of mankind have been the first to perceive, because of their exceptional ability, and which form the basis of the concepts to be learned. Once the Gestalts have been perceived they have also been learned. They will be recognized whenever they occur again, and they can be given names which become elements of language.

That is why the learning and the teaching of physics have the same natural direction as concept formation, from observation to concepts, from experiment to theory and not *vice versa*. They should follow the same direction and the same stages from phenomena through quantities and laws to theories, from the simple to the structural, from the concrete to the abstract. In this way the scheme of concept formation becomes the basic scheme of the natural *experimental approach*, the scheme, which determines the direction and the structure of teaching. And the scheme of logical processes becomes a guide for the analysis of the chains of reasoning involved.

The natural path of learning physics corresponds closely to the way of learning one's mother tongue. Children learn what a book is, when books are given and shown to them, when they get familiar with books and use them. They learn what a house is when they live in one and see others and visit them. In principle, there should not be much difference in learning, for instance, what the moment of inertia is. Once the Gestalt is perceived and identified, it can be given a name.

The hierarchical levels form natural intermediate aims of learning. The study of each level separately can be an integral whole, where all the different Gestalt-perception processes discussed above are dealt with.

Each level is important, but in the study of any single subject, the first level of phenomena is the most important, because there is no other access to the higher levels. This level has an immediate connection with the standard language and its development, since the phenomena and their properties must first be described in terms of the standard language. On this level, a foundation is built for the physical language, including the adoption of the basic terminology on the qualitative level. The experimental approach leads, through idealizations of phenomena, objects and their properties, to a well-analyzed basic vocabulary and creates automatically the need to distinguish from it the terminology corresponding to higher-level concepts, particularly the quantities. Therefore, the linguistic practices of the teacher and the textbook in themselves display the experimental approach – or the lack of it. (Kurki-Suonio & Kurki-Suonio 1989)

On the second level, the experimental approach reveals a systematic hierarchy of quantities, which determines the natural order of their adoption. In order to define a new quantity certain quantities must be known, because the definition is always based on experimental laws obeyed by the known quantities. The concept formation on this level has a tight cyclic coupling with the level of laws. Demonstrations and laboratory exercises are of central importance in this context (Andersson *et al.* 1989; Hautala *et al.* 1989).

On the level of laws, we encounter particularly the question of teaching mathematical ways of representation. The natural direction of concept formation here leads from experimental measurements through numerical and graphical representation to algebraic representation. Graphical representation belongs to the experimental approach as an important stage of concept formation. It is an abstraction, a mathematical representation of quantitative results of concrete experiments, from which it is possible to proceed further to the higher abstraction level of algebraic representation. Traditionally, graphical representation is taught as a concretisation or visualization of abstract algebraic relations. In such a context it is easily felt to be less valuable, because the more abstract and, hence, "more valuable" algebraic representation has been learnt first (Kurittu 1987).

The level of theory is the highest level of aims. It can be reached only by following certain Gestalt perceptions of the great genii, which have resulted in the invention of the basic laws of the theories. In which phenomenal areas this level can be set as a possible aim, depends entirely on the development stage of the pupils. Altogether, a thorough analysis of the curricula would be necessary to work out proper levels of aims for different grades both in the comprehensive school and in the secondary school.

3. Types of reasoning of the theoretical approach

The arrow of the level scheme shows the direction of the experimental approach. The opposite direction shows the theoretical approach, which starts from theoretical models. There the concepts are given as mathematical elements of the theory defined through their mutual mathematical relations.

It is justified to think that the theoretical approach may provide a fast access to a well-structured understanding of wide areas of physics. However, it requires a readiness to highly abstract thinking, which is possible only when the necessary conceptual basis has first been created through the experimental approach, and the hierarchical level of theory has been reached in a sufficient number of different phenomenal areas. Therefore it is not applicable at school; on the fundamental level of instruction, steps following its direction are faults.

The scheme presented offers a basis also for an analysis of the theoretical approach. In this way, several erroneous types of reasoning common in concept formation can be recognized:

Starting from a model. Taking a model as the starting point of the study of some subject, instead of a phenomenon, is the more common the more modern the subject taught. The traditional comprehensive school teaching of electricity offers a clear-cut example (Ahtee *et al.* 1987). The topic is introduced by defining the charge as an excess or deficiency of electrons and the electric current as a motion of electrons: "The current as a phenomenon is a motion of electrons". This means, that the starting point is a theoretical model of electric phenomena, an explanation before one has even identified the phenomena to be explained. (Moreover, the explanation is wrong and must later be "unlearned").

Still, it is well known that Volta invented the phenomenon of electric current, that Coulomb defined the charge as a measurable quantity, and that static electric phenomena were studied much earlier still. It is certain, that those researchers did not wonder at the amount of electrons nor at their motion.

As stated earlier, with the advancement of physics the identification of new phenomena becomes more and more based on theoretical models and the experimentality of the experimental foundations moves further and further away from a genuine observation. As examples one may think of the study of the new kinds of radiation or of the atomic, nuclear and particle physics. The teaching of modern achievements changes therefore easily more and more into the teaching of theoretical models alone. In this way it is possible to give some kind of a general picture of the modern world view and to outline roughly its latest developments. However, once the experimental basis is omitted its very existence will easily be forgotten.

Computer simulation offers a modern, interesting method of instruction. It is a fast and perspicuous way of demonstrating the working principles of theoretical models and of visualizing predictions derived from them. At the same time, it provides an ever stronger temptation to replace phenomena by models as the starting point of the whole study and, thus, to omit nature completely from the teaching of physics.

Defining a quantity on the basis of a model. The dynamics of rotational motion offers a good example. It is common that the quantity representing the rotational inertia of a body, *the moment of inertia*, is introduced by an authoritative declaration, that the expression $J = \sum_i m_i r_i^2$, where m_i and r_i are the masses of the particles of the system and their distances from the axis of rotation, will turn out to be useful.

The significance of this expression for the rotational motion is impossible to grasp, and it gives no indication of how the moment of inertia could be measured. In fact, to call this expression a definition of the moment of inertia is a crude, though common, mistake of principle. It is a prediction obtained when Newtonian mechanics is applied to a model called the rigid body. In order to derive the prediction, it is necessary to know what the moment of inertia is. The expression does not tell that!

Other examples of the use of model-based predictions as definitions of quantities are found in abundance in the examination papers of students. They include attempts to define *the strength of an electric field*[2] by means of an expression based on the Coulomb law and the magnetic flux density similarly by means of the Biot-Savart law and, for instance, the expression for the *capacitance* of a parallel plate capacitor is claimed to be the definition of the capacitance. Again, the error is revealed when asking, how to measure the quantity on the basis of such a definition if the system causing the field or the structure of the capacitor is not known.

Proving a law on the basis of a model. One example found in several textbooks is the "proof" of the law of refraction on the basis of the wave model of light, assuming that it has a well-defined frequency and wave length. According to this doctrine *the model proves* that in the *real phenomenon* the ratio of the sines of the angles of incidence and refraction is constant and equals the ratio of the (phase)velocities of the incoming and refracted light. This ratio is defined as the refraction ratio of the boundary, and it is agreed that the refraction ratio of the boundary of the vacuum and the material will be called the refraction index of the material. There is, thus, also a mistake of the previous type involved.

Refraction of light at a boundary offers a good opportunity to teach principles of physical concept formation and physical thinking. In the same context it is easy to elucidate the relations between the observable phenomenon, the experimental laws and the theoretical models with the aid of demonstrations or laboratory exercises (Hautala *et al.* 1989). The kind of teaching described above turns, however, physical thinking upside-down by degrading the reality of nature into a deficient realization of the theory.

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[2] In the editorial language checking the correct quantity name *the electric field strength* was erroneously changed into this inaccurate expression.

Another example, occurring in many textbooks, is the "proof" of Ohm's law on the basis of a classical model, where the conduction electrons are classical particles moving in the ionic lattice of the metal and where the resistivity of the metal is caused by collisions of electrons into ions. Here the error is even more dramatic, because honest predictions derived from this model are in sharp contradiction with Ohm's law. With this mistake one loses a good opportunity to discuss the development of physical knowledge, the model nature of theories, the limited validity of classical physics and the necessity of a more accurate theory.

Definition of a quantity through a formula. The energy principle of mechanics offers a typical example. Traditionally it is introduced by defining a new quantity, *the work,* as the product of force and displacement (scalar product or the corresponding integral formula depending on the level of presentation). Several pages of the textbook may be devoted to exercises on the calculation of the work without even a hint at any experimentally observable properties of natural phenomena, the representation of which might require adoption of such a quantity.

This procedure leads promptly to mathematical applications but it gives the pupil no idea about the physical significance of the quantity. This teaches the poor pupils that in physics new quantities are introduced by trying out different kinds of algebraic operations with known quantities. Let us multiply, divide, take powers or roots etc., maybe by chance something useful will appear which could be declared a new quantity.

4. The level scheme in teachers' education

For about 10 years we have been developing a course designed for physics teachers. On this course, the level scheme presented above has provided a usable starting point for many kinds of discussions and exercises.

The scheme offers a simple basis for the discussion of the conceptual structure of any physical subject area and for critical analysis of approaches of teaching. With its aid the students can be taught

– to see the conceptual structure of physics and to apply it to the planning of teaching

– to plan exercises and demonstrations suitable for different stages of concept formation

– to recognize the direction of reasoning in the teaching of different kinds of subjects and to proceed from the concrete to the abstract

– to define reasonable target levels for different grades

– to find arguments for the criticism of textbooks and other written and oral presentations as well as for the evaluation of examination papers and other proofs of learning.

The students were given tasks, which made them practise conceptual analysis of physical subjects, formulate sets of problems on specific subjects for given stages of teaching and analyse and classify problems according to their logical types and nature of problem setting. These tasks were prepared and presented either in groups or individually.

In the discussions, the idea of the experimental approach was clarified by considering the teaching of physical subjects on each of the four hierarchical levels separately and by studying the ways in which teaching on a higher level rests on the lower ones. The deviations from the experimental approach encountered in the exercises were analysed by trying to identify in the level scheme the position and direction of the logical steps and chains of reasoning involved. Naturally, the exercises called attention also to the sources the students had been using, mostly secondary school or university textbooks, and the analysis could, thus, be extended to the approaches of these books.

The most difficult part of the exercises was clearly the phenomenon, the very first level of concept formation. Either students chose a theoretical model for the phenomenon, or the phenomenon was defined in the most general way that theoretical knowledge could possibly allow, instead of reducing it into a simple idealized case offering a basis for the first steps of concept formation. Even when a proper starting point was found, it was difficult to proceed stepwise from one level to the next. For instance, on the second level, all possible quantities, up to the most structural theoretical quantities and to the most remotely related ones, were listed, instead of starting from the essential ones and proceeding through refinement and generalization towards higher levels. A logical somersault could, in fact, be made at any stage.

It was remarkable that students with teaching experience noticed much more readily the flaws in the approach. Their participation in the exercises was of considerable help to the younger students.

The development of the students during the course was obvious. The last exercises needed much less guidance and they also led to much more extensive and deep discussions.

The general conclusion from these exercises was that present physical thinking is very strongly bound to the theoretical approach. It penetrates the textbooks and the instruction on all levels. It governs the linguistic practices and motivation of single teaching events and is, thus, inherent in all details.

5. Final comments

The differences between the two approaches may seem negligible. The same "things" get presented although in a somewhat different order. However, it is the order of things that is essential. It is crucial for understanding and physical thinking, whether the results, concepts, laws, mathematical methods etc. are given as declarations, ready formulae and recipes, or whether they are adopted because they are necessary for the representation and characterization of observable properties of phenomena.

Even plentiful demonstrations, presentations of phenomena and practical applications, or excursions and visits to industry as such do not make the approach experimental. The approach is the direction of proceeding, revealed by the interrelations of the teaching events and by the line of thought attached. The experimentality of the approach means, that all concepts arise from the need to represent features or patterns (Gestalts) of the experimental reality, observable properties of phenomena and their experimental laws. Any concept which cannot be shown to be necessary for the representation of the phenomena of nature is too difficult for the teacher and impossible for the pupil. In teaching there must never be such a hurry to explain the phenomena that there is no time to teach the language required for the explanation.

The experimental approach couples everything to observations right from the beginning. It teaches physics as a representation of nature, as an incomplete and inaccurate model with a limited area of validity. It presents physics as a dynamic natural science, which is continually developing, expanding and becoming more accurate.

The theoretical approach presents the natural phenomena as inaccurate, incomplete and poor realizations of the accurate, complete and beautiful theory. It presents physics as a static mathematical science based on mental models given once and for all.

The general educational aims emphasize the differences in the approaches. The theoretical approach offers the pupils the modern models and explanations based on them but not the foundations of this knowledge. If their knowledge was questioned, their only defence would be to insist that this is what was taught at school. This is education into believing in authorities. History offers enough of warning examples of the consequences. The experimental approach does, perhaps, not give as many cognitive models, but it shows how knowledge is born and what are its foundations. At the same time it teaches one to evaluate critically any new knowledge encountered and to reject any unfounded authority.

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