THE CHARACTERISTICS OF THE EXPERIMENTAL AND THE THEORETICAL APPROACH IN THE TEACHING OF PHYSICS[1]

by

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The hierarchical levels of concepts

Physics is a language for speaking about Nature. The formation of physical concepts is basically a perception process like the learning of meanings of words. It is based on pattern recognition, observing and recognizing features in the surrounding world and its phenomena and giving them names. This indicates that the natural way of learning is experimental by its nature. It has the direction from observation to the concepts, from experiment to theory and not vice versa.

Physics, as it is at present, is an immense information structure held together by a few basic theories. In light of its development it can be seen to consist of hierarchical levels of ever increasing generality and degree of abstraction. In the most broad lines one can distinguish four hierarchical conceptual levels which I give the simple titles: 1. phenomena, 2. quantities, 3. laws, 4. theory (-ies).

The first level of **phenomena** is the level of **observation** and **qualitative information**. On this level the objects or systems participating in the phenomena and their surroundings are recognized, characterized and classified. The properties staying unchanged, those changing and those influencing the phenomena are noted and observed. This is also the first natural stage of concept formation where names are given to the objects, phenomena and to their properties.

The second level of **quantities** is the level of **measurement** and **quantitative information**. Observable quantities are defined which correspond to the properties essential to the phenomenon, making it possible to obtain quantitative, numerical information on the system, on the phenomenon and on the surroundings.

The third level of **laws** is the level of **representation** of the phenomena or **systematic quantitative information**. Correlations between the different kinds of quantities are studied with the aid of well-defined **experiments** and interpreted as mutual dependences. They yield experimental laws which can be expressed in numerical, graphical or even algebraic forms. These laws make possible quantitative predictions concerning that particular phenomenon in similar or related circumstances, through interpolation, or may be even extended through extrapolation outside the observed range. Through experimental tests of the predictions areas of validity of the laws are found.

The fourth level of **theory** is the highest hierarchical level of information structure existing only in physics. It is the level of **understanding** and **explanation** of the phenomena. A theory is

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defined in terms of a basic general model system and the basic laws, which are the rules of behaviour of the model. Through proper restrictions of the general model it is possible to work out specific models for different real systems, circumstances and phenomena within the area of applicability of the theory. The basic laws then yield law predictions for the system studied. It is through this **modelling** capacity the theory provides the understanding of different kinds of specific experimental laws.

Although it can be justifiably claimed that only "how" is a possible question, the basic laws of theory constitute such an immense structure of information and possess an almost unlimited power of making predictions of known degree of validity, that it is at least equally justified to understand this level to provide answers to "why", particularly, since even previously unknown phenomena have been correctly predicted.

The directions of approach

It is this structure of hierarchical levels which defines the natural direction of concept formation, of learning and of teaching. This is the direction from phenomena through quantities and laws to theories, from simple to structural, from concrete to abstract. It corresponds closely to the way of learning ones language.

This is not to be confused with the different directions of **logical processes** of reasoning in the creation of physical information which can be described with another simplified scheme. In all details and on all levels of concept formation perception processes are involved which can be analyzed in terms of **induction** and **deduction** steps, induction steps as generalizations from experimental results into theoretical conclusions, and deduction steps as specific conclusions made on basis of the theory, predictions which can be submitted to an experimental test.

The creation of concepts, definition of quantities, inventing laws and developing theory is, however, not a logical but an intuitive process which only afterwards and in part can be analyzed in terms of logics. A genius is needed.

Again this is similar to any recognition of features or patterns which is necessary in order to build up coherent observations from impulses received by the senses and, thus, to create mental pictures which can be given names. There is always an intuitive mental process, an idealization involved. There is no logical necessity in this reduction into the essentials and elimination of noise. Once the features have been recognized they have also been learned. They will be recognized whenever they occur again and they can be given names which form the elements of language.

This is the natural way of learning. Children learn what is a book, when books are given and shown to them, when they are observing books with their senses and using books. They learn what is a house when they live in one and see others and visit them. There should not be much difference in learning what is, for instance, the moment of inertia. Once the pattern or the feature is observed and recognized it can be given the name.

The level scheme has an arrow of direction which I call the experimental approach. It indicates the direction of concept formation. The opposite direction, which starts from theoretical models based on concepts given just as mathematical elements of the theory defined through their mutual mathematical relations, I call the theoretical approach.

It is possible to think, even justifiably, that theoretical approach may provide a fast access into a well-structured understanding of wide areas of physics. It is, however, obvious that it requires a readiness to highly abstract thinking. It is not suitable at school and there is no other way to introduction of basic physical concepts than the natural, experimental approach. Every one needs at first a mother tongue.

The experimental approach binds everything into observations right from the beginning. It teaches physics as a representation of the nature with a limited area of validity, incomplete and inaccurate by its nature. It presents the physics as a dynamic science, which is developing and getting ever wider and 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 science based on mental models given once for ever.

Experiences from a teachers' course

The level scheme gives a simple means for critical analysis of approaches. We have been developing for about 10 years a course designed for physics teachers. There this scheme has been applied as a basis of many kinds of discussions and exercises.

The conceptual structure of specific physical subjects and subject areas have been analyzed. Particularly the treatment of the subject on each of the four hierarchical levels has been discussed and the ways in which the treatment on a higher level rests on that of the lower ones have been studied.

The aim has been to help the students

- to see the conceptual structure of physics and to apply it on planning of their teaching
- to plan exercises and demonstrations suitable for different stages of concept formation
- to recognize directions of reasoning and to proceed from concrete to abstract
- to define reasonable target levels of teaching and
- to get a basis for criticism of text books and other writings as well as for evaluation of their pupils' writings

A general conclusion from these exercises has been that there is a tremendously strong mental binding into the theoretical approach. It penetrates the textbooks and physics teaching in general on all levels. Of course, as a result, it dominated the thinking of the students participating the course. Even conscious efforts to revert the direction of approach have lead only to formal revisions like increase of laboratory exercises and demonstrations, visits to industry, etc. The theoretical approach is still present in all details, it governs the lingual practices and the motivation of single teaching events, and it is inherent in all detailed steps of reasoning.

In the exercises the most difficult part was clearly the phenomenon, the very first level of concept formation. Either a theoretical model was taken for the phenomenon or the phenomenon was formulated in the most general way made possible by the theoretical knowledge only, instead of the reduction to the simple idealized case offering the basis for the first concepts. 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 they easily listed all possible quantities, up to the most structural theoretical quantities and to the most remotely related ones, instead of starting from the essential quantities and proceeding through refinement and generalization towards the higher levels. The logical somersault could, in fact, be made at any stage.

It was remarkable that students with teaching experience much more readily noted the flaws in the approach. Their responses to the exercises also helped considerably the younger students.

The development during the course was almost dramatic. The last analyses needed much less guidance and lead also to much wider discussions.

The idea of experimental approach was clarified by seeking and pointing out examples of the opposite. Several typical patterns of inherent theoretical steps in the approach were noted and classified.

Starting from model instead of phenomenon

Taking a model as a starting point instead of a phenomenon is the more general the more modern is the subject taught. One of the most common examples is to start the treatment of electricity by defining the charge as an excess or deficiency of electrons and the electric current as motion of electrons. This means starting from a theoretical model of electric phenomena, from an explanation before any recognition of the phenomena to be explained. Still every one knows that Volta invented the phenomenon of electric current and Coulomb was able to define the charge as a measurable quantity, and that static electric phenomena were studied even much earlier. Those researchers did certainly not wonder why there are too much of electrons or why do the electrons move.

Defining a quantity on basis of model

For instance, it is very common that the moment of inertia, the quantity presenting the rotational inertia of a body, is adopted just by a solemn authoritative declaration: the expression $J = \Sigma m_i ri^2$ will turn out to be useful and is called the moment of inertia. It is impossible to understand the significance of this expression for the rotational motion, and it gives no indication of how the moment of inertia can be measured. In fact, it is a crude error to call this expression a definition. It is a prediction obtained for the moment of inertia when Newtonian mechanics is applied on the model called the rigid body. It is certainly necessary to know what the moment of inertia is before one can make any prediction for its values.

Other examples of this error are found in abundance from examination papers of students. It is common to define the electric field strength by means of the Coulomb law, the magnetic flux density by, for instance, the Biot-Savart law and even the capacitance with the expression for the capacitance of a parallel plate capacitor. The error becomes obvious by asking, how to measure the quantity on basis of definition if the system causing the field or the structure of the capacitor is not known.

Proving a law on the basis of model

One example found in several textbooks is the proof of Snell's law on the basis of the wave model of light, assuming a well-defined frequency and wave length. It is, thus, taught that this model proves that in the real phenomenon the ratio of the sines of the angles of incidence and refraction must always be equal to the ratio of the velocities of the incoming and refracted light. This ratio of velocities is then defined as the refraction ratio of the surface or the refraction index of the material if the light is coming from vacuum. There is, thus, also an error of the previous type involved.

Another example 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 to the ions. You can find such proofs in many textbooks. The error here is even more dramatic than in the previous example, because honest predictions derived from this model are in sharp contradiction with Ohm's law. With this error a good opportunity to demonstrate the limited validity of classical physics and the necessity of new theories is lost.

Definition of a quantity through algebra

The energy principle of mechanics offers a typical example. Many textbooks start by defining a new quantity, the work, just by a formula. Several pages can be offered to discussion of how to calculate values of this quantity in different cases without even a hint to the experimentally observable feature in natural phenomena which would require adoption of such a quantity.

This teaches to the poor pupils that in physics new concepts can be found just by trying different kind of algebraic operations with known quantities. Let us multiply, divide, take powers or roots, may be something useful will appear!

Final comments

One can analyze the different approaches in many more ways and recognize the two directions in many details. The experimental approach, or the lack of it, can be seen in the lingual practice of the teacher. This will be discussed in another paper presented in this symposium (Riitta and Kaarle Kurki-Suonio, Lingual analysis and exercise in the education of physic teachers).

The role of the graphical representation can be seen in two ways. The traditional theoretical way is to introduce the graphical representation as a concrete visualization of abstract algebraic relations and to proceed then to the interpretation of the graphs.

In the experimental approach it is one step in the formation of abstract concepts, an abstract representation of quantitative results of concrete experiments. The algebraic representation is then a further higher abstraction. When understood and developed in this way the graphical representation becomes important, while in the theoretical view it is easily seen as being less valuable, because the more abstract and, hence, more valuable algebraic representation is learned at first.

One can also draw attention to the order in which quantities are adopted. The experimental approach reveals a systematic hierarchy of quantities. Certain quantities must be known before some new quantities can be defined, because definitions of the new quantities are based on experimental laws obeyed by the known quantities. This would, however, be a subject for another paper.

If we wish our pupils to understand physics we should never adopt new concepts as declarations or base their definitions on something which is more abstract than the concepts themselves. Every such concept will appear to the pupils as mere mysticism. Understanding is possible only if all concepts arise from the need to represent observed and recognized features of the experimental reality, properties of objects and phenomena or their experimental laws. Any concepts which cannot be taught in this way are too difficult. In teaching there must never be such a hurry to explain the phenomena, that there is no time to teach the language required by the explanation.

HIERARCHICAL LEVELS OF CONCEPTS