Understanding basic physical concepts – which? The Modeling of Real World Phenomena Based on Laws of Physics

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Abstract

In the process of teaching students basic concepts of physics, it turns out that the first problem is not the introduction of new concepts but the underlying use of physical quantities and the formulation of relations between them. While it is clear that in the teaching process a careful introduction of new concepts is necessary, in an attempt to convey to students the right "feeling" about their meaning, less emphasis is given to formal manipulations of physical quantities as mathematical entities which are needed in practical problem solving.

Our research's goal was to determine which are the main problems and obstacles that students encounter in acquiring a working knowledge of physics. A study was conducted among freshmen who had combination majors mathematics-technology, chemistry-biology and biology-home economics, and the fourth-year students who had combination majors physics-technology and physics-chemistry. The results of this study show that the weak links are often the "accessory" and "subsidiary" knowledge needed in addressing physical problems.

Not only is a proper approach needed in teaching, but maybe additional training is necessary for teachers in order to avoid, in the teaching process, a mechanical use of formulas leading to a superficial knowledge without a satisfactory understanding, also in the sense of existing passable (open) channels between various pieces of knowledge. Our intent is not to go deeper into explanations of the topics of the physics curriculum, but to give students more time to gain a general view of the structure of interwoven pieces of knowledge and to consolidate their knowledge.

1. Introduction

Even though physics, as a scientific and technical discipline, enjoys a considerable reputation in public, it seems that the teaching of it has become rather unpopular at all levels, from K-12 to college. From elementary school on, students, except for a small minority which has a particular talent for physics, find physics more or less unnecessary and physics classes difficult or useless.

In the present article we are addressing the general education of physics and not the physics for physics majors.

The basic question, asked by students from the beginning of their physics classes, is what to do with physics. They don't have a clear picture about what to expect from physics instruction and where to place physics in a broader context. At the same time they feel that physics is a "high" scientific discipline, inaccessible by ordinary people. An imitation of a "scientific" behavior and acting "like a scientist" seems to them exaggerated and they are not eager to imitate it, because they would feel ridiculous.

On the other hand the teachers of physics feel that the lack of interest in physics is not deserved, that not enough time is given to the teaching of physics, and that it should be broadened and intensified. Especially during the implementation of the Bologna reform it is clear that in college-level science programs not much time and emphasis will be given to physics. On the contrary, the teaching of it will have narrower time frame and will face greater competition from other (for example general education) subjects.

In such conditions it is necessary to investigate in what ways can the teaching curriculum be made more attractive and successful not only for students who are particularly interested in physics, but also for a broader audience. Therefore, it is of basic importance to determine what are the basic physics content knowledge and skills that students should learn to master. Searching for an answer, we encounter different levels of knowledge and content. Distinguishing them is important in the structuring of content and methods of teaching (Glynn and Duit, 1995).

To start with, we can state that the knowledge of phenomena and skills in measuring procedures represent only the outer shell of what students should learn about physics. Maybe we could, somewhat pretentiously, say that the basic purpose of the teaching of physics, especially at below-college level, and to non-physics majors, is the modeling of the workings of the real world and the creation of the scientific part of the view of the world. This kind of knowledge should not be reserved exclusively for "professional physicists", but should rather be the main objective of the physics instruction from its beginning. This just means that in studying phenomena we focus more on the underlying structures and principles of the world than their manifestations.

In the following sections we present what we consider to be the essential elements of the teaching of physics, if it is to successfully present physical explanations of nature.

2. Phenomena, concepts, quantities and connection

The basic physics instruction usually starts with a description of familiar phenomena (accompanied by suitable experiments). Based on these phenomena general laws of physics are discovered. Students learn these laws, use them to understand other phenomena, and solve related problems.

Here we encounter a basic sequence of steps leading toward "knowledge":

phenomena → concepts → definitions → (*feeling*) *→ manipulation → problem solving*.

Each step should be accompanied by the important factor of understanding (Feynman, 1966).

The scientific observation of phenomena is a systematic perception of the real world. It demands some capacity for registering of those aspects that are the most essential for a particular phenomenon. Based on observations of the real world basic concepts are created. These are mental constructs, general concepts that we create (possibly with help of others), 'basic building blocks', 'atoms' or 'components' of a theory. Often we don't fully understand basic notions and often they are difficult to explain. Nevertheless, they are the starting points of any theory and are, despite not being always completely clear, important tools in problem solving. Every theory creates 'its own' concepts. A change of concepts as mental elements changes theories. In turn, changes of theories cause revisions of the concepts.

Directly from the concepts definitions are formed. They formulate concepts in a precise way, listing all their essential properties and characteristics. While in the formulation of concepts often no precise formulation is given, definitions are as a rule given rigorously. As a consequence, in more demanding definitions, 'rote memorization' often replaces understanding. All physical quantities (e.g. position, coordinates, velocity, acceleration, kinetics, energy, temperature, heat, electric current, etc.) are notions, precisely determined through definitions, and are the result of mental forms created by observation and quantitative treatment of physical phenomena.

A good 'feel' for natural phenomena and as a consequence an instinctive element of an understanding of how the nature is functioning, follows from a good understanding of concepts and definitions. On this basis we can understand and appreciate, at the first glance controversial, so called Wheeler's first moral principle (Taylor and Wheeler, 1992): "Never make a calculation until you know the answer!" His further comment: "Make an estimate before every calculation, try a simple physical argument (symmetry! invariance! conservation!) before every derivation, try the answer to every paradox and puzzle. Courage: No one else needs to know what the guess is. Therefore make it quickly, by instinct. A wrong guess brings the refreshment of surprise. ..." Let us add that a good 'feel' for the workings of phenomena is of essence also for a good feel in establishing a relationship to physics.

The next step is to a greater degree of a technical nature. It is a "manipulation" of concepts and definitions, or of introduced physical quantities. In physics curriculum students learn how to treat phenomena "quantitatively". Already Galileo Galilei believed that all phenomena can be understood on the basis of general laws of nature which can be formulated mathematically. Laws of physics are just quantitative relations between different physical quantities. (For example, the Second Newton's Law connects the acceleration of a body to forces acting on the body.) If we treat physical quantities as abstract mathematical quantities, we can, through mathematical operations, "simulate" events of nature and, by using laws of physics and appropriate initial and boundary conditions, calculate quantities of interest. (We are aware of the fact that the "logic of empirical statements is not the logic of mathematical theory". Still, it seems reasonable to consider physics, especially from the educational point of view, as "the science devoted to discovering, developing and refining those aspects of reality that are amendable to mathematical analysis", see Ziman (1978).)

This brings us to the last step, to problem solving. A physics problem or a question means that out of given data (or data obtained by measurements) we are expected to find certain other quantities. A solution means that we arrive from data to quantities requested in a problem or a question. We have to find relations between known quantities and the unknown quantities that the problem asks us to find. This is done through the use of laws of physics which are, as we stated earlier, relations between different physical quantities. In simple problems connections are simple and can be written in "one line" or with "one formula". More demanding problems, though, require several steps, with several lines and formulas, in order to arrive from the data to desired quantities. Harder problems require clearer picture and understanding of the content of laws of physics on which the solution is based. Solving a problem therefore means a search for quantitative connections between data and desired quantities. Those connections are written mathematically as equations.

3. Which are basic physical concepts?

Usually the teaching of physics means that students get acquainted with basic notions appearing in all standard main areas of physics, starting with so called "classical" physics (without the relativity theory). These are mechanics, thermodynamics, electricity and magnetism, light and optics. Then (within time constraints) modern physics follows. It includes the relativity theory and some basics of quantum mechanics.

Even though the treatment of these at no stage of school curriculum goes in depth (except for physics majors), it is clear that a presentation of basics alone requires a significant number of suitable concepts and definitions. At that it is important to realize that most of the time the problem is not an intuitive understanding of notions that students are mostly familiar with from everyday life, like path, speed, acceleration, temperature, heat, electric current and voltage, etc. The problem is to create an overview of all different notions and a realization that it is details which are of decisive significance for the correctness of a certain idea and its treatment. For example, for most students, it is not easy to distinguish between velocity and speed (which is the magnitude of the velocity), displacement and path, uniform motion and uniform rectilinear motion (which is the only unaccelerated motion), temperature and heat, etc. The question is whether under conditions of severely limited time available for instruction it makes sense to insist on the mentioning of all the topics which are (usually) part of school curricula and presented in a majority of textbooks (like for example Serway, 1996).

We believe that the goal of physics instruction is more than a presentation of all topics of the classical and modern physics a creation of a "physical" view on the nature. Under "physical" view we understand an interest in structures of reality as they stem from laws of physics, rather than specific facts about a multitude of specific phenomena. It is quite clear that it is impossible to present all specific findings about the nature as they have accumulated until now through scientific research. It is possible, however, to create an overview over what is happening in nature, i.e., to group natural phenomena according to laws of nature which determine the course of certain phenomena (Feynman, 1966).

When we talk about structures we think about functional connections between quantities and relationships between them. This makes sense, since we saw that laws of nature occur as functional connections between physical quantities. Equality of structures of course means the same underlying mathematical description which does not depend on the specific nature of respective quantities. Equality of structures also means the equality of equations and therefore their equal solutions. As R. P. Feynman (1966) put it: "The equations for many different physical situations have exactly the same appearance. Of course, the symbols may be different—one letter is substituted for another—but the mathematical form of the equations is the same. This means that having studied one subject, we immediately have a great deal of direct and precise knowledge about the solutions of the equations of another."

The recognition of the fact that everything occurring in nature happens in accordance with a few (relatively) simple laws of nature which are obeyed by all phenomena in nature is of paramount importance for our world picture: "Nowadays, as superstitions are again spreading, it is important to show in schools, without religious fervor, the long-reaching significance and the universal validity of laws of physics. The end of an introduction to mechanics is a wonderful opportunity to do that. A child does not grasp immediately that there could be laws of physics that are valid uncompromisingly. However, the most basic law is the fact that there are no magic tricks in nature. Some people do not want to believe even that." (Kuščer, 1979)

Thus, in a multitude of phenomena, structures are created based on laws of physics, which allow a grouping of seemingly very different phenomena, which can be distinguished and yet grouped together on the basis of the structural understanding about the functioning of nature. The same Newton's law, for example, can explain such different phenomena as the motion of the planets around the sun, and the sound. Thus high-level synthesis knowledge is formed.

This, of course should not be applied in the same way for all levels of the teaching process. At lower levels it is important that children learn how to systematically observe nature and to establish a connection between physical concepts they encountered, and to receive, during physics instruction, a more precise formulation and a wider knowledge. First, familiarizing with phenomena prevails over the recognition of structures. At higher levels it becomes more and more important to discover structures of nature, i.e. connections between diverse phenomena which obey the same laws of physics.

If we decide that the goal of physics instruction is to create clear structures which contain all phenomena (that we are able to explain), a somewhat different approach to teaching offers itself, i.e., to treat phenomena based on the similarity of laws that govern them. This means that, while it is important to establish a familiarity with some set of basic pieces of phenomenological knowledge, it is important to establish interconnections between them rather than to enlarge that set.

These connections occur inside physical concepts, but they also need to reach outside of the realm of physics. When we use mathematics in the quantitative treatment of physical phenomena, we also have to understand structures. For a "simulation" of a phenomenon we use mathematical manipulation of physical quantities that stem from equations that connect them. Thus, in the teaching of physics it is important to establish nets of connections between concepts and quantities. "Connectivity", the number of connections, is more important than the number of concepts alone.

4. Difficulties

Giving a questionnaire to students of combined majors mathematics-technology, chemistry-biology, biology-home economics, and mathematics-computer science, we wanted to find out where students encounter the greatest difficulties in their use of the knowledge of physics, i.e., when they are solving problems. We wanted to see where are "bottlenecks" and where can the situation be improved. Among the most frequent reasons for problem solving blocks the following were listed.

1. poor knowledge of mathematics (75 %)
2. students don't find the "right formulas" for the given problem (73 %)
3. the inability to "set up equations", i.e., mathematically formulate the relationships between physical quantities that appear in the problem (67 %)
4. a lack of knowledge of the area of physics that appears in the problem (65 %)
5. a lack of knowledge of concepts that appear in the problem (63 %)
6. a lack of understanding of notions that appear in the problem (41 %)
7. a lack of understanding of "formulas", i.e., "why should two quantities be related by such a formula" (21 %)
8. a lack of interest in physics (13 %)

From the answers it is apparent that students feel that the greatest difficulties lie in the lack of knowledge of mathematics, which includes, besides a lack of purely mathematical skills, an inability to *translate* connections and relationships, which they know how to describe in words, into a mathematical form, i.e., into equations

Here it is clear that we don't always deal with a lack of knowledge of mathematics, but rather with an inability to *use* mathematical knowledge, which they *do* have in purely mathematical context also in non-mathematical environment. Mathematics does enable one to solve physics problems operatively. However, mathematical manipulations alone are far from being sufficient to solve them. For example, 75 % of students correctly calculated the extremum of the function $y(x) = ax/(b + x)^2$. A week later they found that an electrical device in a circuit uses power $P = RU_g^2/(R + R_n)^2$. When asked when the use of power was maximal, only 17 % answered correctly.

The situation is similar when "setting up equations". Virtually all students know the meaning of proportionality – if the variables y and x are proportional, then $y = kx$, where k is the coefficient of proportionality. When asked to describe the motion of a boat which comes to a stop in such a way that its acceleration is proportional to its speed, only 17 % of students were able to write the correct relation.

Therefore it is of fundamental importance that the knowledge acquired in any subject is not limited only to the subject itself. To this aim, an emphasis on connections between physical notions and quantities, and mathematical procedures is very important in physics instruction.

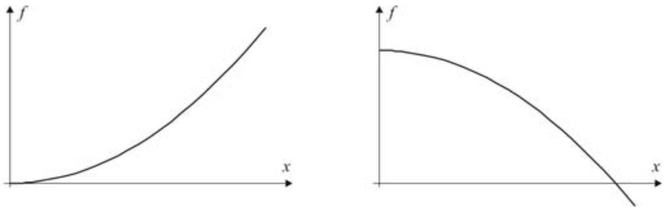
But it brings certain difficulties and the following are some examples.

1. Newton's Law of gravitation and Coulomb's Law. The gravitational force between two particles (with masses m_1 and m_2 separated by a distance r) is given by Newton's Law, $F_g = Gm_1m_2/r^2$; the magnitude of electric force between two charges (q_1 and q_2 at a distance r) is given by Coulomb's Law, $F_e = k_eq_1q_2/r^2$. Both laws have the same functional form and similar consequences (not identical, as there is only one type of masses and two types of charges).

It is interesting that the introduction of the gravitational law in the framework of mechanics does not cause any difficulty: the law is totally 'acceptable' and understandable. The same is true for Coulomb's Law presented in the framework of electricity. However, there is lack of understanding or acceptance if Coulomb's Law is presented together with the gravitational law (after all, say the students, the material "unjustifiably" reaches into a material that has not been "covered"). Similarly, the same happens to the gravitational law when it is presented along with Coulomb's Law (since the students have "already forgotten" the material from mechanics to which they are entitled after certain time). This is particularly clear when introducing the analogy between the electric and gravitational field. While the introduction of electric field (**E**) via the equation $\mathbf{F_e} = q\mathbf{E}$ is "acceptable" and does not pose problems, students are not at all ready to view, in the analogous equation $\mathbf{F_g} = m\mathbf{g}$, **g** (the free-fall acceleration) as the "gravitational field". In this case it is clear that students view the new manifestation of the same notion as something completely new. This means that one of the principal goals in physics instruction – the ability to recognize structures, as opposed to the knowledge of separate phenomena – is not achieved.

2. The slowing down of a boat and the discharging of a capacitor. A kinematics problem asks how a boat slows down if the deceleration is proportional to the speed. The solution is a speed that decreases with time exponentially. After finding the solution to this problem, students were asked a similar question in a different context: what was the current in a circuit with a capacitor and a resistor, if the time derivative of the current was proportional to the current. Virtually no help came from the analogy between the two cases.

3. Question: The figure below shows two parabolas. What phenomena can be represented by the two graphs? The given answers involved many quantities for which we can only say that they change, but certainly not as a quadratic function. For example, the answers included the path of a uniform motion, the charging and discharging of a capacitor, the warming and cooling of water.



As it is clear that the students know a lot about "mathematical" parabolas, the answers clearly show that no connection is made between their concept of the mathematical world and any other mental environment.

5. Conclusions

The physical picture of the world and the "physical" approach to problem-solving based on the recognition of structures, rather than single phenomena, i.e. manifestations of the underlying structures, enable students to confront problems of any kind (not just problems in physics) in an analytic-synthetic way. Stated simply (Feynman et al, 1966), "The same equations have the same solutions." A simple consequence of this fact is that the recognition of structures makes it possible to construct *models* (which are formally describable by equations). A few models may cover many different phenomena from many different contexts. The structural knowledge obtained at the physics instruction is therefore helpful in solving any problem with the same underlying structure.

A model is a simplified (and therefore tractable) representation of a restricted feature of the real world. The modeling of natural phenomena is very important, both in science and in education. However, it has not the same importance in all instances. For example, when introducing and describing simple phenomena (like rectilinear uniform motion), it does not seem necessary to introduce intermediate stages in terms of "models" which are sometimes more complicated that the phenomenon itself. In such cases, "modeling" may even obscure a clear and simple picture that students already have about a phenomenon. (It may still be appropriate to introduce models about simple phenomena as prototype-models.) When describing complicated phenomena, the use of models is unavoidable: they convey a simplified, yet both acceptable and tractable qualitative information.

Therefore, in order to make the instruction more efficient, it is necessary to reduce the number of separate topics ("non multa sed multum"), and at the same time keep stressing the "underlying unity of nature" i.e. the similarity of rules, according to which sometimes apparently different phenomena behave. The same rules of course mean analogous behavior.

It seems reasonable to regard the instruction of physics as a modeling, not only of single phenomena, but of the physical reality as whole. The scientific part of the "view of the world" is nothing but a "meta-model" of the fabric of reality.

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