The Study of Physics for Non-Physicists

T. Kranjc

Faculty of Education, University of Ljubljana, Ljubljana, Slovenia
tomaz.kranjc@pef.uni-lj.si

1. Introduction

Natural sciences, and technology based on them, have enormous influence on our everyday life. In our research we wanted to determine the level of scientific literacy of students, especially of students of the Faculty of Education, who will themselves teach natural sciences in elementary and high schools. What is their knowledge and understanding of basic concepts and principles of science? We were particularly interested in their familiarity with the "modern" areas of physics.
We conducted a series of tests (using questionnaires) among students with combination majors mathematics-technology, chemistry-biology, and biology-home economics. In their freshman year those students take 120-165 hours of physics for non-physicists (60-90 hours of lectures, 30 hours of computation practicals, 30-45 lab hours). We assessed their knowledge and understanding of a) some basic concepts that were covered in physics lectures and were very much emphasized in class, and b) some generally known facts from physics that were not included in physics lectures. We also assessed the motivation of students for study, and their interest in physics.
We tried to determine which methods of study are acceptable to students and effective, considering students' prior knowledge and general scientific literacy, and thus successful in acquiring deeper knowledge of certain topics. Different study materials (chapters from textbooks, new texts, Internet) were made available to the test group that showed greater motivation for studying, and we were available for help and consultation to the same group.
A basic problem seems to be students' lack of motivation for study, and a lack of study habits, which they should have acquired in their previous study in elementary and high school, as well as the general attitude of society towards natural sciences and technology.

2. The opening questionnaire

For students who enroll in the natural sciences departments of the Faculty of Education, this is not their preferred choice, but rather an option, available to them because of their performance at the end of high school. Less successful students can only choose less competitive majors which have less restrictive enrollments, even though this is not necessarily a reflection of their talents. This choice is due to their weaker preparation, poor working habits and a lack of motivation. The university education process itself has no influence on that. It should be underlined, however, that this concerns the average; among the students enrolled in the sciences departments there are, every year, also some very talented and motivated students.
The level of knowledge of entering students, and the knowledge that they demonstrated in their senior year at the university, are shown in the graph below. The left columns represent freshmen, the right ones seniors. The first questionnaire contained simple questions from the following topics:

1. Graphs of rectilinear motion
2. Newton’s third law
3. Gravitational force and “weightlessness”
4. “Weightlessness” on Earth
5. Astrology – do you believe in it?
6. The twin paradox – do you believe it?
7. Levitation in a gravitational field
8. A simple pendulum in “weightless” conditions
9. A mass-spring oscillator in “weightless” conditions
10. The telekinesis of Geller: do you believe in it?
11. Forces on Earth orbiting around the Sun
12. The first law of thermodynamics
13. Heat engines
14. Entropy
15. The mains voltage
16. Electron velocity for 100 eV (100 GeV) energy
17. The age of the universe
18. Black holes

The percentages of right answers are shown in Figure 1.

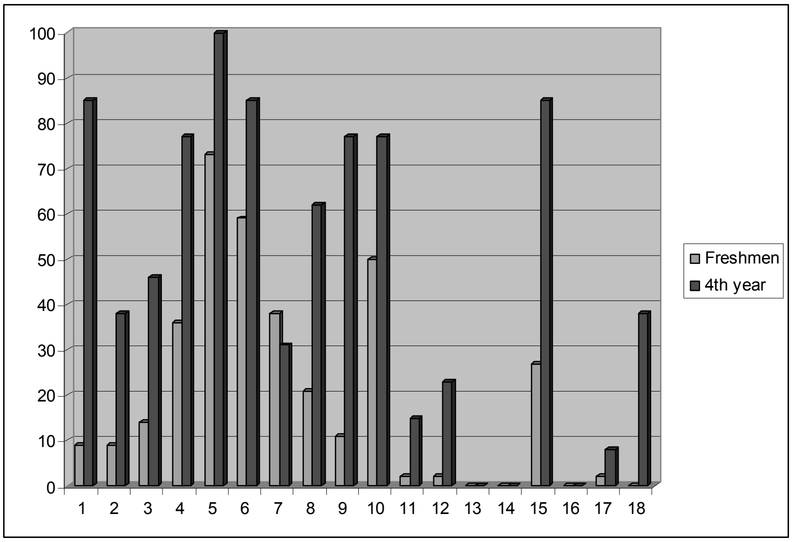

Figure 1: Percentage of correct answers to the first questionnaire.

The graph shows a weak knowledge of entering students and, unfortunately, of seniors as well. Therefore it is necessary to find ways to improve the learning success.

Learning is the process of acquiring and storing knowledge. According to Piaget, this process is the creation of ‘self-regulating’ symbolic structures which develop through processes of ‘assimilation’ and ‘accommodation’. Here assimilation means the change of perceptions through existing structures of knowledge, while accommodation is the adaptation of structures of knowledge to received perceptions. The basic building blocks of cognitive structures are overt actions which take place in the real world. When such activities are internalized so that they can be performed “in thoughts” and become systematic, then they become the "stuff of reasoning". Knowledge itself is not yet understanding. Understanding means the ordering of separate pieces of knowledge into a system: this is achieved through the creation of transitional channels between building blocks of knowledge, through their coordination, which makes an overview possible, their interchangeability and the possibility of their manipulation, generalization and creation of syntheses. Understanding is connected with the ability to explain phenomena. This is possible only on the level of formal reasoning and hypothetico-deductive thinking. In the course of study the "collection of knowledge", the process of storing learned facts and routine manipulations of those facts (e.g., solving physics problems through the use of formulas that fit data the best, and their use based on previously learned procedures) is not questioned. However, in physics, we emphasize the importance of *understanding* and focus on it, as only this makes possible an effective use of knowledge, not just for familiar types of problems, but also for unfamiliar and "unexpected" ones. Understanding is also tied to (more) long term retention. We have to add right away that "learning by memorization" (i.e., rote memorization and "drill") is not harmful and is necessary (often *unavoidable*). Many basic facts don't need any special understanding and only need to be memorized. And they *do* need to be memorized, otherwise they cannot be used operatively (and therefore effectively). The mistake, however, is if we are satisfied with learning only facts and routine procedures required by given material, by "rote memorization" and without real understanding.

3. Main problems

The knowledge of physics acquired in school is not always connected to understanding (Fig. 2, see Sec. 4). Some difficulties during study are related to poor understanding of general (not just physics) notions and some are specific to physics. The following are possible barriers to reaching a good understanding of the material:

1. unclear general concepts (interrelation of quantities, functions)
2. misinterpretation of experience, misconceptions about some everyday phenomena, misunderstanding
3. persistent perceptions, sometimes promoted by non-physics contexts and/or terminology.

A lack of understanding of the physics content often leads to an apparent conflict between the use of "common sense" and the use of "physical logic", which seem to contradict one another. Students arrive at the (false) notion that the laws of the physical world do not apply to everyday experience and do not explain it, and that one has to unplug common sense and plug in "physics sense" when physical phenomena are described. This consists of the use of "procedures" which they get used to applying on the basis of processed sample examples. As a consequence, when they describe physical phenomena, they seem to be dealing with a world outside their experience rather than using the knowledge of physics to explain conclusions based on that experience.

Non-understanding of basic concepts can lead to a "chain reaction", when non-understood concepts are used to define new composite (again non-understood) concepts.

Among general notions the non- or poor understanding of which often presents a significant barrier for students, we shall discuss the example of (mathematical) *functions*, which play a central role everywhere where connections (especially quantitative ones) between different quantities occur. Physics is precisely the search for connections between different physical quantities and the ability to manipulate them. Therefore, the understanding of physics is hardly possible without the notion of function. "The book of nature is written in the language of mathematics" (G. Galilei).

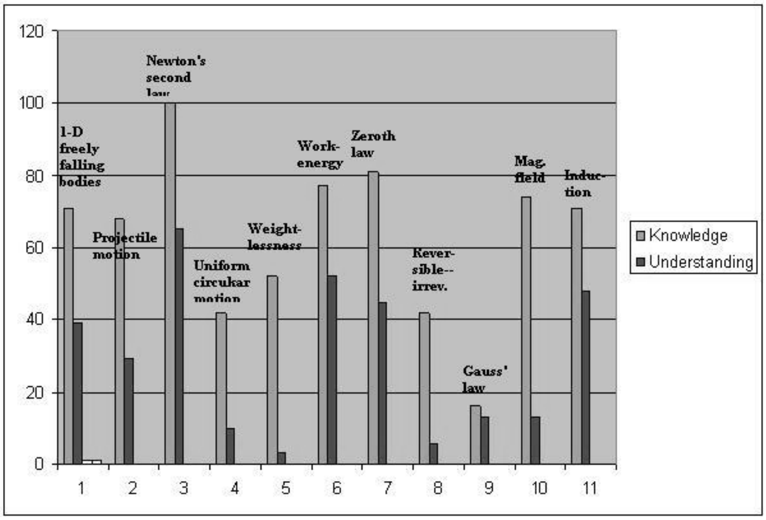

Figure 2: The gap between "knowledge" (of sheer facts) and understanding for some common topics in physics.

The dynamics of uniform circular motions is among specific problems from physics that are based on falsely interpreted experiences.
As an example of false perceptions, supported by non-physical contexts and/or terminology, we shall discuss the weightless state

3.1. Functions

The concept of a function is "*abstract* in its very essence" [3]. Students are familiar with mathematical functions from their previous schooling. They are able to find zeros, poles, asymptotes of complicated functions, and draw their graphs. Doing that, they encounter a variety of fundamental difficulties (related to the understanding and not to the technique of function manipulation):

a) not distinguishing between variables and constant values of variables
b) not distinguishing between a quantity and its change (i.e. between a function and its derivative)
c) inability to relate abstract functions to actual phenomena.

Students encounter functions in a very pure form at the beginning of their physics lectures in the chapter on kinematics. Kinematics starts with a treatment of the one-dimensional motion of a point mass, where the notions of position of a point in space, its velocity and acceleration are introduced as functions of time, $x = x(t)$, $v = v(t)$ in $a = a(t)$. Students learn to represent functions by graphs and know the meaning of those graphs. Thus, they show mastery in manipulating the graphs as in Figure 3 and know how to find qualitatively the two remaining graphs if one is given.

However, it turns out that the mastery of drawing and interpreting graphs from Figure 3 does not imply the ability to explain the meaning of the velocity graphs of Figure 4 and the corresponding acceleration and position.

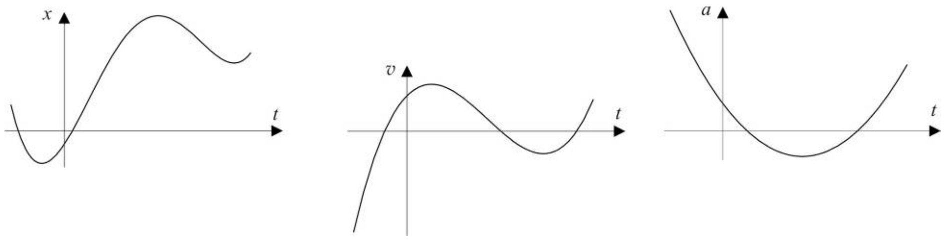

Figure 3: Coordinate, velocity and acceleration; from anyone of them students are able to deduce the other two.

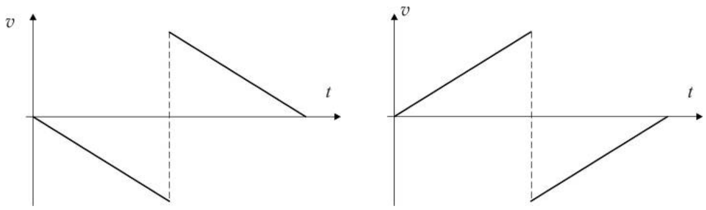

Figure 4: What is the acceleration?

While they see that the acceleration is constant, they transfer the discontinuity of the velocity to the same kind of discontinuity of the acceleration.
The task of graphing the velocity of a harmonic oscillator, as a function of the distance from the equilibrium (phase portrait in phase space), seems to be very demanding.
They find it difficult to graph thermodynamic processes for different pairs of thermodynamic variables (for example, to graph $V = V(T)$ for Carnot cycle for which $p = p(V)$ is known).
We can summarize the barriers toward true understanding as follows:

- students know the techniques, but lack understanding (feeling)
- they are unable to use their knowledge of mathematics in non-mathematical contexts
- they do not recognize *structures*

3.2 Uniform circular motion

A typical example of a phenomenon, where a wrong interpretation of experiences leads to a false understanding, is a uniform circular motion. Already children encounter early in their lives the feeling of being pulled out while turning (on a merry-go-round or moving through turns), by a "certain outward force". Early on they hear that this force is called the "centrifugal force". Later, when they learn in school that every circular motion needs a *centripetal force,* which points towards the center, they still have in their mind the notion, supported by their own experience, that in a circular motion there is a "centrifugal force". They put together both forces which add up to zero, getting a contradiction they cannot explain.
Related to circular motion is the notion of "weightlessness". A centripetal force acts on an astronaut who is *circling* around the Earth. They explain the "weightlessness" by claiming that the gravity force acting on an astronaut at high altitude, where his space vehicle orbits, is "negligible". However, they cannot explain, why, despite zero force, the astronaut circles instead of moving along a straight line. The term "weightlessness" for a free-floating body is an example of inappropriate terminology which is misleading.

4. Common points

We tried to research characteristics of difficulties, in the acquisition of knowledge and understanding, through a series of questionnaires where we assessed a) knowledge (questions regarding definitions, descriptions), and b) understanding (questions asked to clear some misconceptions), see Fig. 2.

Common characteristics of the majority of difficulties in the acquisition of knowledge and understanding can be conceptually grouped as follows.

- Lack of connection between experience and physical analysis
- Impracticable channels between various pieces of acquired knowledge
- Lack of coordination between various pieces of knowledge (lack of structure and unifying system)

We can add to that a bad social and psychological study environment. Students are not used from their previous schooling to regard learning as work that is needed for successful study, the same way physical training is necessary for success in sports. Poorly and erroneously understood or realized "student-friendly" schools can have bad consequences for work habits and standards that are set by students themselves. Consequences of poor knowledge are also lack of self-confidence and certainty in solving specific problems. Thus, some additional barriers on the road to successful study are

- expectation of easy solutions (adding together previously prepared pieces of solutions)
- bad working habits
- uncertainty about the correctness of a solution (no feeling)

5. "Therapy", portfolio

Achieving success in study is similar to achieving success in sports. While in sports it is clear to everybody that there can be no success without hard (and often monotonous) work, the same is true in study – "Practice is the way to understanding". The following aspects of study turned out to be important for success:

- reading textbooks
- devoting serious effort to solving a few exemplary problems
- taking time to thoroughly think about various aspects of a problem, and working out and mentally *reconstructing* the phenomenon
- filling gaps between previously unconnected pieces of knowledge
- carefully examining a problem to discover that "common sense" reasoning is in agreement with "physics logic" which reinforces one's self-confidence in problem-solving
- discovering that by learning science one realizes its explanatory power for everyday phenomena and its technological usefulness
- realizing that the study of science produces the scientific literacy needed for the understanding of technological and to some degree societal reality.

The method of portfolio practice has been shown to be the most successful method for non-physics majors in physics courses [4]. The creation and the use of portfolios (a part of each portfolio was a set of problems with solutions completely "discovered" and constructed by each student) turned out to be a strong motivation factor and a useful tool, which noticeably improved the success of students who used it compared to students who did not.

Comparison of results for students with and without portfolio, for three typical problems (from kinematics, thermodynamics, and electromagnetism, which were considered difficult by most students) are shown in Figure 5. Some reasons for such a significant improvement due to portfolio creation have been discussed elsewhere [4].

We conclude with the remark that, in conditions where motivation and work habits are a major hindrance to success in study, portfolios appear to be a powerful tool for improving motivation and intensify the study, and with that, the scope and the depth of knowledge.

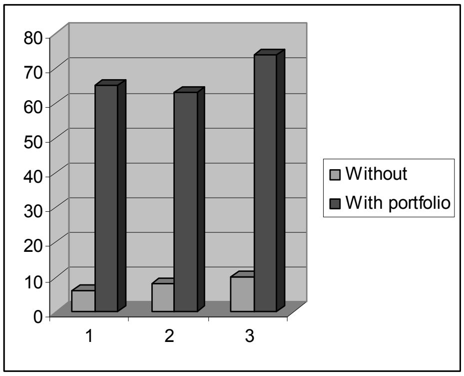

Figure 5: Students who worked on their portfolios during the school year demonstrated a markedly higher ability to solve problems (which were based on greater understanding and higher working skills)

6. Conclusion

We tried to draw attention to some basic, frequently encountered problems in the study of physics for non-physicists. We have shown that the use of portfolios may increase motivation and learning outcomes. However, for better long-term results, a change in attitude of the state towards science education and in the general social climate regarding science, as well as an improvement in the social status of teachers, would be necessary.

References

[1] Flavell J H 1963 *The Developmental Psychology of Jean Piaget* (New Jersey: Princeton)

[2] Piaget J 1954 *The construction of reality in the child* (New York: Basic Books)

[3] Penrose R 1987 *Emperor's New Mind* (Penguin Books) p. 66-67

[4] Gitomer D H and Duschi R A 1995 Moving Toward a Portfolio Culture in Science Education in *Learning Science in the Schools* (New Jersey: LEA Publishers), pp. 299-326