WHAT FRACTION OF PUPILS REALLY REACH THE STAGE OF FORMAL THINKER IN PHYSICS?

Rudolf Krsnik, Planinka Pečina, Maja Planinić, Ana Sušac, PMF, Physics Department, University of Zagreb, Croatia
Ivica Buljan, Primary school “Zapruđe”, Zagreb, Croatia

According to Piagetian theory transition from preoperational stage of thought to the concrete operational stage occurs between 7 and 11 years of age. Around age 11 child is concrete thinker; she or he is capable to think causally and that is of crucial importance for physics teaching. Concrete operational mental structures permit intuitive conservation reasoning, reversal thinking, multiple classification, assimilation of data from concrete experience and their arrangement and rearrangement into serial ordering etc. However, thought operations of concrete thinker are strictly related to objects and physical processes with which he is in direct physical contact and are directly tied with physical experience. Objects and environment themselves are not of crucial importance; what is important for cognitive development is the child's activity in acting on those objects. However, concrete thinker is not able to think on the basis of verbally stated hypothesis and abstractions.

With further cognitive development to the stage of formal thought operations these limitations are outgrown. Formal thinker has no need for objects and direct physical experience; she or he is able to think in abstractions using propositional logic. While the earlier stages were described in terms of domain specific descriptions, it was not so with the formal stage. Formal operational stage was described in terms of operational schemes, i.e. certain patterns of reasoning, for example:

- focusing on the important variables what includes isolating relevant variables and controlling variables in a given process;
- formulation and stating of hypotheses to concepts and abstract properties and the use of propositional logic;
- combinatorial reasoning,
- proportional reasoning,
- stating functional relationships, etc.

According to original Piagetian theory [1,2] transition from concrete operational stage of thought to formal one is a) universal and b) occurs between 11 and 15 years of age. Numerous results of research in the light of Piagetian ideas have showed that the first statement does not hold. It turned out that ability of formal thinking strongly depends on context inside which development has occurred. In the second statement Piaget was too optimistic. It was shown later that large fraction of adults still stay at the stage of concrete thinker. As school children are concerned it turned out that less than 20% students of English comprehensive schools are in late formal stage at age 16 [3].

There exists certain criticism of Piagetian stage theory, for instance that it is not explanatory but descriptive. Nevertheless, Piagetian stage model is very useful and simple enough for the use in physics teaching. One important reason for that is the fact that in majority of Piaget's original questions in tests and clinical interviews are about physical objects and processes. There is more or less consensual agreement that dynamics of child's cognitive growth is strongly dependent on the quality of teaching process. Stage model gives to curriculum developers and teachers important informations of two kinds. Knowing cognitive level of students (by their age) one can: a) choose appropriate level of teaching contents, and b) structure and organize teaching contents in a manner which can accelerate student's cognitive development. Piaget himself claimed that physics is in that respect the most convenient of all school subjects.

Our experiences with pupils of all ages and with university students (future physics teachers) demonstrate significant difference between those who has attended traditional teacher centered teaching and those who attend pupil centered constructivist oriented teaching.
The great majority of interviewed students attended some of traditional teacher centered teaching during their schooling. The achievement of middle school students is in accordance with quoted results of Shayer et al [3]. Their data, that not more than 20% students age 16 are formal thinkers, is particularly interesting. Namely, we have found that in teacher centered teaching process (lecture) only about 20% of students try to follow the lecture longer than 5-10 minutes; the others switch themselves off. Also, according to Solomon [4] percentage of English school students who are able to think about physical problems in appropriate manner is about 20%. Coincidence of these data cannot be accidental.

Students in higher classes up to age 19, and even university students (future physics teachers), in certain situations do not handle some operations which are associated with formal thinking. It seems that these inadequacies are tied with weak qualitative understanding of concepts which have been acquired mostly via definitions and mathematical formalism. It is often difficult to discriminate what is the reason of inadequacy in response: undeveloped formal thought operations or undeveloped conceptual structure. We will consider in more details few typical examples restricted to thought operations of isolating and controlling variables.

- Definition of electrical resistance, $R = U/I$, student interprets in the following manner: "Electrical resistance is proportional to voltage and inversely proportional to current." Obviously, student is not using control of variables, but he does not understand the concept of electrical resistance either. It is indicative that such mistakes are often made by future teachers of mathematics and physics (and not by future teachers of physics, physics and chemistry or physics and technology); it probably reflects their way of thinking in mathematics.

Similar and even more drastic case, but fortunately less frequent, is the interpretation of second Newton law, $F = ma$, by stating: "Force is proportional to the mass of the body."

- In answer to question how does centripetal force depend on radius $r$, most of students choose one of the answers: "inverse proportional" (led by equation $F_{cp} = mv^2/r$), or "proportional" (equation $F_{cp} = m 4\pi^2 \rho / T^2$). One could say they are just not applying control of variables, therefore they are not formal thinkers. However, the other possibility is that they have not at disposal sufficient conceptual understanding of given situation, and that could be the reason they are not able to apply formal thinking.

- Isolating relevant variables is particularly important operation in qualitative reasoning on properties of harmonic oscillator.

a) In the first case system is simple harmonic oscillator, a weight suspended on elastic spring. The task is to find functional dependence of free oscillations frequency in dependence of relevant parameters of the system (i.e. dependence $v_0 \propto \sqrt{\frac{k}{m}}$). In spite of the fact that there evidently exist only two relevant parameters, $k$ and $m$, student have lot of troubles with their isolation (these parameters were known to students, but were not mentioned in the formulation of the problem). While isolating relevant parameters is a serious problem for appreciate part of students, procedure of dimensional analysis is not a problem at all.

b) Interesting case is analogous procedure for simple pendulum, i.e. to find out functional dependence $v_0 \propto \sqrt{\frac{g}{\ell}}$ using dimensional analysis. Here is the operation of isolating relevant parameters more complicated and more challenging. Namely, beside the length $l$ of a thread as the obvious parameter, immediately appears the mass $m$ of the bob (which turns out not to be relevant parameter for frequency, and should be eliminated in the later procedure), and gravitational field of the Earth, $g$, which is hidden at least at the first glance. Majority of students succeed in isolation of $g$ as a relevant parameter only after additional questions (why is the bob swinging at all?).
In the course of our (constructivist oriented) variant of school curriculum in 11th class (age 17) the problems are stated to find functional dependence of speed of (sound) wave on relevant parameters in stretched wire, and in bulk specimen. Students, future physics teachers, working on that curriculum have serious problems in autonomous isolating relevant parameters which could influence the speed of the wave. Probable reason for these difficulties lays in the way how they were educated. They have learned physics mostly following traditional lectures, using definitions and mathematical approach without appropriate qualitative reasoning.

In the case of stretched wire ($v \propto \sqrt{\frac{T}{\mu}}$) it should be easy to isolate the length $l$ and the mass $m$ of wire (which enter in the relation through linear density $\mu = \frac{m}{l}$ and tension $T$ of thread; it is really difficult to anticipate some additional relevant parameter.

In the case of bulk specimen ($v \propto \sqrt{\frac{E}{\rho}}$) students have even more problems in isolating relevant parameters because they are more abstract. Only a part of the students succeed in autonomous isolating of these parameters, but only when during discussion they are reminded that analogy should be drawn with simple harmonic oscillator and parameters which characterize inertia and elastic properties of the system respectively. Isolating of elastic constant $E$ (or some other modulus) makes more difficulties than isolating of density, because it is more abstract.

How to improve formal thinking of pupils in physics? We see the solution in interactive, student centered and constructivist oriented approach to the physics teaching. That is necessary for achievement of science literacy of all scholars; in the same time that is useful for the most able as well because they have more opportunity to express their special abilities. For example, in 4th class (age 10) elaborating experimental theme on water waves, we asked pupils one inappropriately difficult question: One boat drives with speed 10 km/h, another one with speed 20 km/h. Both of them produce water waves. Compare the speed of waves produced by these two boats. On our surprise there were pupils (4%) who answered that speed of both waves are equal, because wave speed should depend only on properties of water.

It seems that majority of scholars from age 11 to the end of middle and high school (age 18-19) are mixture of concrete and formal thinker. Certainly, the portion of formal thinking part is increasing with age, but is far from being completed. Consequences for physics teaching could be that it is always convenient to start with gaining physical experience, and through discussion move towards generalizations (but not strictly by inductive method). The development of formal thinking is strongly dependent on context, so in teaching practice (and curricula development) Piagetian ideas about cognitive stages should be combined with perception on preconceptions and conceptual change, and complete teaching process should be subjected to the ideas of educational constructivism. In such educational surrounding pupils are unbelievably able participants. For example, in 8th class (age 14, second year of physics teaching) during experimental treatment of light dispersion, Newton's experiment of light dispersion on prism was presented and historical situation in Newton time was described, particularly old ideas that white light is primitive and colored light is a mixture of white light and of something else. Pupils were told that Newton created two crucial experiments by which he succeeded to refute that old ideas. Pupils were asked to create these two crucial experiments themselves (by the use of two identical prisms, light source and a screen with a small hole). With the help of some discussion (answers to pupil's additional questions) and a small assistance of teacher pupils succeed in creation of both crucial experiments. In spite of the fact that it was paradigmatic change in historical development of physics, which had many difficulties with acceptance, pupils took it as a quite normal thing. Pupils obviously had no strong preconceptions about that matter and this result was hardly conceptual change to them. This result is on the line with important constructivist thesis that knowledge is dependent on social
surrounding. By the way, such way of teaching process is not limited to very small number of exclusively able teachers (what is occasional comment of uninformed persons, even physicists). In our case the role of teacher was taken by two students on pre-service teaching practice.

References