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# The Structure of Knowledge and Students' Misconceptions in Physics

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**Abstract.** Misconceptions are beliefs that contradict accepted scientific knowledge but they are seemingly supported by commonsense arguments. Misconceptions in physics attest the lack of recognition of existing physical correlations but improper ideas can often be found in their place. From testing of misconceptions, we have deduced, that they are also related to the structure of knowledge. Some basic rules (the rule of completeness of information, the knowledge of closely related ideas, the existence of entire trains of thought, and the thorough knowledge of basic principles) were identified as a tool for the elimination of the students' misconceptions, a distinct guidance to the prevention or elimination of misconceptions is proposed based on this.

## INTRODUCTION

Misconceptions are beliefs which contradict accepted scientific theories [1]. They cause characteristic difficulties in the instruction of natural sciences subjects for example physics, chemistry, biology, and mathematics is not an exception either [2,3]. Misconceptions in physics give seemingly true explanations for correlations and phenomena, but they actually are not consistent with the experiment. They are based on superficial, commonplace considerations. All teachers face student's misconceptions, but it is not guaranteed, that they think of the necessity of taking conscious action against them.

Misconceptions tell about a lack of recognition of existing correlations, in simplified terms, a lack of understanding. We find an improper idea instead of correct knowledge. Their elimination calls for a conceptual change, in other words, for another evaluation of the problem [4]. Correction can be aided also by a persuasive experiment.

The misconceptions are seemingly supported by obvious arguments. The source of misconceptions is frequently some practical experience [5]. Students rely on this, mainly in lower classes. They already have some misconceptions before starting their physics studies [6]. The role of experiences collected in the initial phase of physics education is particularly dominant [7]. Misconceptions emerging in the higher classes can arise out of arbitrary considerations and can form a part of a multifaceted thought system.

In the literature we can meet the terms "misinterpretation" [8] and "preconception", etc. In my opinion, within the concept of misconception it must be included that they are supported by certain arguments, and also the appearance of misconceptions on the basis of evaluating information should be incorporated into the definition. Therefore, I recommend to accept a definition, pursuant to which misconceptions are beliefs, which contradict scientifically recognized theory, but are seemingly well-founded on the basis of some practical experiments or logical conclusions.

Scientific literature describes misconceptions from all areas of physics, from mechanics [9], thermodynamics [8], optics [10], to the theory of relativity [11], quantum-physics [12] and astronomy [13].

In this paper, the most important observations of my research on misconceptions along with the conclusions and proposals drawn from them are presented. The tests are related to the mechanics of solid bodies and hydrostatics. The results of tests, as those of other investigations show that misconceptions often contradict even the most basic

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physical principles [1] (e.g. to the basic laws of dynamics and the basic laws related to hydrostatic pressure). That may lead to incorrect statements in many situations.

## MISCONCEPTIONS REVEALED BY THE TESTS

The questions for mechanics came from Hestenes well-known Force concept inventory test of 29 questions [7, 14]. This test is oriented on the same basic concepts and laws of kinematics and dynamics, e.g. the concept of velocity and acceleration, the concept of force, Newton's second law, features of projectile motion and collisions, the knowledge of centrifugal force, the role of friction and of the air-resistance, as well as the motion in space. The test was taken by students from three high-schools (age group of 15 year) and 22 first grade college students (19 year olds), 114 respondents altogether.

186 students from three high-schools (15 year olds) took part in the hydrostatic test. That test consisted of 14 questions and besides of my own questions it contained also questions known from earlier researches of Loverude, Heron and Kautz [15]. The tasks mainly required a comparison of pressure in the certain points, e.g. in "N" shaped and "L" shaped vessel, in Torricelli's experiment, in communicating vessels and in the "U" shaped vessel with two liquids (water and mercury). The essential difference compared to the mechanics-test was that a brief explanation of the students' conclusions was also asked. Note, that hydrostatics hasn't already been the part of curriculum in the secondary school, the students meet relating knowledge only in 7$^{th}$ grade.

Students in both cases had an hour to fill in the test.

### Typical Results from the Mechanics

In the following some typical questions of the tests are presented to support the conclusions drawn from them.

It is very meaningful that 85% of the 9$^{th}$ grade students, 80% of the 11$^{th}$ grade students, and 82% of the college-students explained the motion of a vertically thrown ball by a *decreasing upward-force* being exerted to the ball. This is the cause of the decreasing velocity of the ball. The question was the following [7]:

"A boy throws a steel ball straight up. Disregarding any effects of air resistance, the force(s) acting on the ball until it returns to the ground is (are):

(A) its weight vertically downward along with a steadily decreasing upward force.
(B) a steadily decreasing upward force from the moment it leaves the hand until it reaches its highest point beyond which there is a steadily increasing downward force of gravity as the object gets closer to the earth.
(C) a constant downward force of gravity along with an upward force that steadily decreases until the ball reaches its highest point, after which there is only the constant downward force of gravity.
(D) a constant downward force of gravity only.
(E) none of the above, the ball falls back down to the earth simply because that is its natural action."

87% of the 9$^{th}$ grade students and 73% of the 11$^{th}$ grade students believed, that the force of the kick is exerted to the golf ball during the entire time of its flight. The right answer was found only by 20% of the 11$^{th}$ grade students and 8% of the 9$^{th}$ grade students. Something very similar happened in the group of college students, where 18% of the responders gave the right answer and 77% the wrong answer. A question concerning the motion of a golf-ball taken from [7]:

A golf ball driven down a fairway is observed to travel through the air with a trajectory (flight path) similar to that in the depiction below (Fig. 1). Which following force(s) is(are) acting on the golf ball during its entire flight?

1. the force of gravity 2. the force of the "hit" 3. the force of air resistance

(A) 1 only (B) 1 and 2 (C) 1, 2 and 3 (D) 1 and 3 (E) 2 and 3

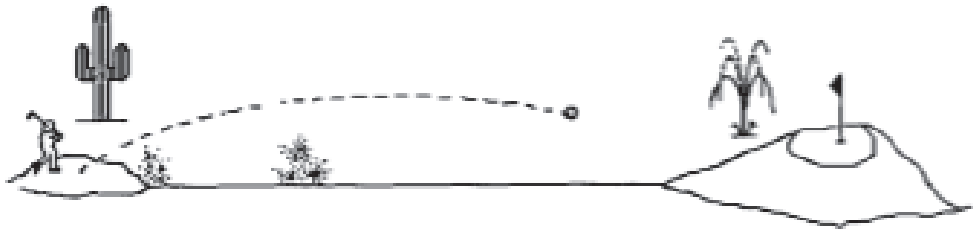

**FIGURE 1.** The trajectory of a golf ball [7]

Considering both answers in the case of the golf-ball and vertically thrown ball, it is clear that student's answers do not result from any fortuitous consideration. Students connect the possibility of motion to a force acting permanently. That error had also been persistent for a long time in the Aristotelian physics, where the cause of motion was explained by the *impetus* (the force that results in or causes motion [16]). In fact, it is about ignoring of the law of inertia.

The construction of further questions cannot be reviewed because of lack of space. It turns out, that in the question regarding the motion of the elevator, a significant part of the students associate an extra force with motion, because 79% of the 9$^{th}$ grade students and 57% of the 11$^{th}$ grade students gave the answer, that the rope exerts bigger force to the upward-elevator (frictionless uniform motion) than it does if the elevator is at rest.

A serious failure appeared also in relation to the law of action-reaction. 50% of the 9$^{th}$ grade students and 66% of the 11$^{th}$ grade students did not consider this law relevant in the case of the collision of a truck and a car. In another question, 45% of the college students believed that the "active" force is bigger than the "passive". This can be concluded from the task in which two students are sitting in rolling chairs and one of them pushes off the other. The students believed, that the first (who is regarded as the active participant of the scene) performs bigger force.

These results evince that students used Newtonian concepts of mechanics in a limited way. According to the authors of the test the conceptual threshold for the understanding of Newtonian mechanics is a result of 60% of their test [7]. The mean scores, analysed in the paper were the following ones: 48%, 64% and 42% at the "regular" level, 56%, 78% and 66% at the "honors" level of high schools.

## Typical Results from Hydrostatics

In the test of hydrostatics [**17**], students did not recognize that the pressure at the same level (in the continuous liquid) is the same. Some respondents assume that the effect of the atmospheric pressure is higher at the points of the liquid nearer to the contact surface of liquid and air, e.g. $p_C > p_B$ and $p_B > p_A$ at the Fig. 2a) and $p_D > p_E$ at the Fig. 2b). Other respondents could not add the atmospheric pressure to the hydrostatical pressure of the liquid in the N-shaped vessel (the respond $p_C < p_B$). It is clear from the explanations of the answers. This is called the Torricelli's Theorem problem. This means that the students are not aware of the connection of Pascal's law, the principle of communicating vessel and the depth-dependence of hydrostatical pressure. The above mentioned deficiencies could not be found in only 14% of cases. Students also had a problem with comparison of pressures when in the Torricelli's tube was closed air (Fig. 2c). 37% of students thought that $p_A > p_B$ and 40% of students thought that $p_B > p_A$. The solution was very simple on the basis of the principle that the pressure in the points at the same level must be the same.

In the U-shaped vessel with a variable cross-section (communicating vessels) the students had to mark the level of the liquid in case of balance. A very high rate of the students (57%) believed that the level of the liquid in the thicker stem should be lower. This suggests that students connect the pressure of liquid to the *whole amount* of liquid in the branches of the vessel and based on this, they think of some balance. We can see that students don't apply the rule of the pressure in communicating-vessels. The question was answered correctly only by 29% of the students.

It was also observed, that when calculating the pressure of the liquid in the horizontal branch of the "L"-shaped vessel, the students did not calculate with the pressure of the liquid in the vertical branch of the vessel (e.g. $p_A > p_B$ for the Fig. 2b). It is evident that students do not apply the basic knowledge about depth-dependence of the hydrostatic pressure, they do not know its relation to Pascal's law. Their knowledge about depth-dependence of pressure could be easily confused.

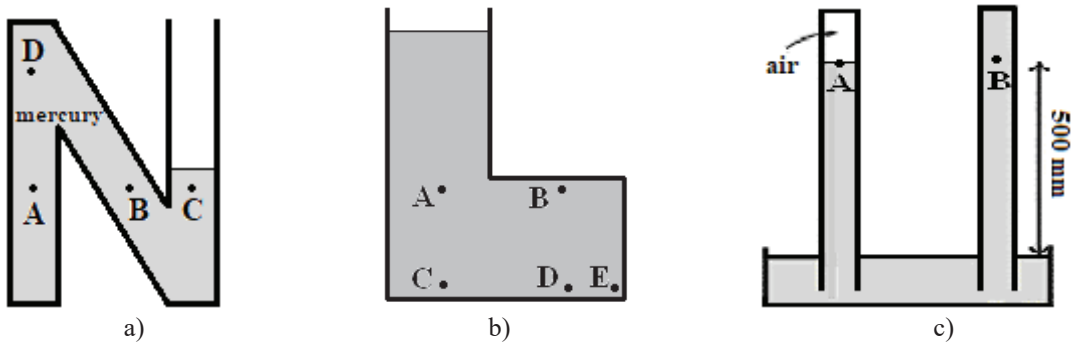


**FIGURE 2.** Vessels from the test [8]

In the examined hydrostatic problems, one of the cause of the failures was that students probably do not treat the pressure as a scalar physical quantity.

## THE ROLE OF THE STRUCTURE OF KNOWLEDGE

From the character of students' errors, we can deduce that misconceptions reflect a *special* deficiency of information. This deficiency may mean a deficiency of the knowledge of facts and a deficiency of the knowledge of relationships between some knowledge's. Hereinafter, we will examine, what kind of relation exists between misconceptions and structure of knowledge. I'm rely on the assumption that if a student has all essential information and he/she knows all relations of factual knowledge, the emergence of misconceptions is excluded.

Presumably, no misconceptions would occur if students would have all essential information related to the given problem. Regarding the flight of a golf-ball students create misconceptions (they believed that the force of the kick is exerted also without close contact) because they assume that motion is impossible without acting force. This idea indicates a problem regarding the law of inertia. In the case of collision of a truck and a car students have a problem regarding the law of action-reaction. They are unaware of these laws or its knowledge has pure formal character. Both laws play a key role in physics; the lack of their knowledge excludes a realistic analysis of the situations mentioned above.

The knowledge is in most cases based also on some previous knowledge but the new knowledge may have also its own essential, indispensable elements. In case of teaching a new piece of knowledge (e.g. projectiles, collisions) the teacher must analyse whether the students will be at disposal of all essential knowledge necessary to understand the given problem. Teachers should think over the question of **the completeness of information**. It is an important part of their didactical work. The teaching process of projectile motion and collisions must include the explanation of relations to above mentioned laws.

The hydrostatical test pointed to the problem with the knowledge of connection between partial knowledge. The incorrect answers refer to the fact that partial pieces of knowledge in the thinking of students regarding hydrostatical pressure are not connected in a way that they could support each other in a more complicated situation. Because of this, students do not apply either the depth-dependence of hydrostatical pressure, the principle of communicating vessels, or the law of Pascal. In the case of "L" shaped vessel we see that the basic knowledge of depth-dependence of hydrostatical pressure must be used together with the Pascal's law. The relevant knowledge of the topic (the pressure) constitutes a coherent whole, in which the failure of the use of either link can lead to questioning the whole knowledge. This aspect is called **the question of closely related ideas**.

Complicated concepts (e.g. the pressure) are a coherent whole of certain partial knowledge content. A lack of understanding connections between them, means an insufficient knowledge of the concept. The existence of bindings should be definitely clarified; this is the task of the teacher [17].

The possibility of arising misconceptions is also influenced by the fact, whether students passed through certain critical points of the considerations while investigating certain questions. If they do it then the possibility of misinterpretation is smaller. This is **the role of the entire train of thought**. A good example is the case of the principle of communicating vessels. If we emphasize the role of the pressure when discussing communicating vessels, and also form the connection with the hydrostatic paradox, the students will have a more comprehensive and more secure knowledge of the principle. When discussing various topics, it is worth for the teacher to think over the characteristic trains of thought, he wants his students to follow.

The question of a whole train of thought is also related to the question of reducing the curriculum below "critical mass". The reduction of the curriculum does not help students, on the contrary, in certain cases it may make the reaching of our goals more difficult. There are skills that cannot be superficially mastered. Getting through some critical points in a given topic means the complete understanding of a coherent train of thought, in other words, the knowledge of a whole set of frame-knowledge and their relations.

The essential basic set of knowledge in a given knowledge-system is represented by its basic principles, which pervade the whole system and from which all essential elements of the system can be deduced. The knowledge and crystallization of basic principles help understanding and at the same time the repetition of misconceptions can be avoided. Therefore, we must clear up the **corroboratory role of basic principles**. We can enforce their positive impact in the phase of the systematization of the curriculum. Students must consider the basic principles as solid and unquestionable strongholds, whose recognition crowns collected knowledge. Certainly the students can be led to the basic principles only considering their age. But the teacher can led students towards the understanding of basic principles and can enforce their guiding role already in the phase of planning.

## CONSIDERATIONS ABOUT HOW TO PREVENT AND ELIMINATE MISCONCEPTIONS

In the previous paragraph we identified important causes of the emergence of misconceptions which are related to the structure of knowledge. Misconceptions can also be created in the special case when the source of the error is the judgment of things from a wrong point of view. This raises **the question of the right approach to the problem**.

In the hydrostatical test, the comparison of air-pressure in the closed area above the mercury and outside of vessel was a difficult additional question (Fig. 2c). The question regarding closed air can be considered from the viewpoint that the air is pressured by the mercury, which is pressed in the vessel by air outside, or from the viewpoint that it is prevailing a decompression thanks to mercury which is trying to go down due to weight. Students were not able to do the right decision, and just 9% solved this question properly.

This question can be illustrated bay another example from my experience occurred during an estimation of electrical resistance of a wire, when a student concluded that the thicker the wire the greater its resistance is. Since a clever student committed this mistake, it arose my suspicion that she found a viewpoint that actually made her answer logical. It turned out, that she thought that the role of the wire is *to resist* rather than *to lead*. So the “more” wire there is (even in terms of cross-section), the greater the resistance is.

These cases show vividly that particular approaches to the physical problems may exist that might lead to a false conclusion. Because of this it is important to be able to formulate a good question about a problem. Good questions draw attention to the essence of the problem, and bad questions distract us from the essence.

During my teaching experience I came to another consideration useful to prevent and eliminate misconceptions. Some crucial introductory knowledge is worth teaching even in the period when the misconceptions associated with them have not been developed. In this sense, we can talk about an **early prevention of misconceptions**. Such a suitable system of knowledge should be established in the early stages of teaching physics and in the foundation subjects (e.g. nature studies) respectively. It is worth finding the age-appropriate forms of relevant knowledge. You can already talk e.g. about the relativity of motion in the sixth grade, the relationship between inertia and friction can be outlined, one can talk about the fact that the experiments that take place on trains have the same outcome as the ones taking place in a resting state. One can also mention that no current is generated in the conductor if it is not moving relative to a magnet. We should highlight the consequences of such basic information. Of course, it is inevitable to provide less complex information at a younger age, and to get back to that topic later with a more detailed explanation.

In some cases, students have access to the essential information necessary to understand the problem, but they do not alter their earlier improper views. On the contrary, they draw conclusions on the basis of insufficient information. Thus, it can be concluded that **the development of critical thinking** can be an efficient tool for preventing misconceptions.

## CONCLUSION

The idea of relation between misconceptions and structure of knowledge is the central recognition presented in this paper. This relation has not yet been investigated in the literature as far as I know. Using this approach some category of the systematic description of the reason of misconceptions can be also revealed (completeness of

information, closely related ideas, whole train of thoughts). Based on this, some didactical and methodological tools were proposed to help students to resolve their typical epistemological difficulties. In my opinion with the use of these concepts a guideline can be also generated for improving the structure of text books through which misconception can be avoided more easily. All this requires a proper assessment of the students' level of knowledge. Of course, the thoughts propounded in this paper should be strengthened with further work.

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