From fortune-telling to engineering: how to implement physical concepts

A. Van Deynse

University College Ghent, Faculty of Applied Engineering Sciences, B-9000 Ghent, Belgium
(Annick.VanDeynse@hogent.be)

Abstract
The rapidly changing technology and the new developments in engineering call for changes in the settings, contexts and methods of engineering education. Besides disciplinary knowledge, training different skills and competences is more and more a point of interest. But due to the rapid changes, a good comprehension of disciplinary knowledge of i.e. physics and mathematics is also important. It ensures that the "new" engineers are able to solve complex problems adequately. In this article, a method to enhance the insight in physical concepts is described.

At the beginning of the semester the students can fill in a multiple choice test, based on the known "Force Concept Inventory", to detect possible misconceptions. During the semester, the students prepare the laboratory experiments profoundly and can test their initial knowledge about the subject by answering some concept questions. Adequate feedback at this stage is provided as the questions are rather for instructing purposes than for testing. The implementation of the necessary physical concepts is tested at the end of the semester by a reprise of the initial multiple choice test and a theoretical test about the performed experiments. A profound analysis of these results indicates the effectiveness of the method.

Keywords: Physics, concept questions, work session, testing.

1. INTRODUCTION

The rapidly changing technology and the new developments in engineering call for changes in the settings, contexts and methods of engineering education. Besides disciplinary knowledge, training different skills and competences is more and more a point of interest. But due to the rapid changes, knowledge of i.e. physical concepts and mathematical methods is also important, as the "new" engineers must be able to solve complex problems adequately. In the work sessions physics we emphasize therefore on both implementation of the necessary disciplinary knowledge and development of research skills. By performing physical experiments the students train, among others, to collect data using an appropriate measuring method, to interpret the results using error analysis and to present their findings clearly in a written report or an oral presentation. Next to learning to plan their work and developing a critical attitude, they are also responsible for the assessment. This is conform the CDIO^{TM} standards [1], the used guideline for good engineering education.

The American Association of Physics Teachers [2] also published a guideline, "Goals of the introductory physics laboratory". The five goals they identify to teach are:

- The "art of experimentation" (designing experiments)
- Experimental and analytical techniques
- Underlying concepts
- The basis of physical knowledge
- Collaborative learning skills.

These goals are more specific for the physics laboratory but also in good agreement with the CDIO^{TM} standards.

So next to developing good research skills, attention has to be paid to the basis of physical knowledge and the underlying concepts. In this article we describe a method to deepen the understanding of the physical knowledge apart from the development of the research competences.

2. METHOD

2.1 Setting and teaching method

The work sessions physics have evolved from "making a report about a physical experiment" to a more diversified approach using different active learning techniques [3].We have however noticed that the insight in the underlying physical concepts of the performed experiments is rather poor. This can be concluded from the results of the written theoretical test, related to the experiment, at the end of the semester [3]. As physics is the basis for most engineering sciences, it is therefore important to pay attention to these concepts during the preparation for the work session.

Herewith we must bear in mind that each student, entering a first course of physics, possesses a system of beliefs and intuitions about physical phenomena derived from extensive personal experience. This system functions as a common sense theory of the physical world which the student uses to interpret his experience, including what he uses and hears in the physics course [4]. Conventional physics instruction fails almost completely to take this into account. The common sense theory leads to intuitive preconceptions developed in the student's mind even before entering formal physics courses, the so called misconceptions [5].

To deal with the above stated establishments, we opted to use aspects of the Just in Time Teaching method [6] in order to both detect the misconceptions as to get a better understanding of the physical concepts. Just-in-Time Teaching (JiTT) is an active learning method designed to facilitate student engagement with and reflection on course material prior to arriving in the classroom. The first step in the JiTT cycle is for students to answer web-based questions related to their reading. This JiTT method has proven its effectiveness for the theoretical course in introductory physics [7], [8].

The developed method is based on the first step of the JiTT method. To make a list of the possible misconceptions and the initial physical knowledge, the students can perform a short multiple choice test at the beginning of the semester. This test consists of 6 questions from the known "Force Concept Inventory" (FCI) [9] (see also appendix). The questions are translated in Dutch, the native language of our students, for a better understanding. No feedback is provided at this stage; only the final score is communicated. Before entering the work session, the students have to prepare the physical experiments profoundly. Traditional pre-laboratories are derivations of equations or calculation of the results using sample data. This preparation is elaborated with a test on the physical concepts related to the experiment. The students can answer a few concept questions on Dokeos, the electronic learning platform used at the University College Ghent. The concept questions are presented as multiple choice questions and adequate feedback is provided at the same time as this test is rather for instructing purposes than for testing.

2.2 Research method and evaluation instruments

The developed method is based on the first step of the JiTT method. To make a list of the possible misconceptions and the initial physical knowledge, the students can perform a short multiple choice test at the beginning of the semester. This test consists of 6 questions from the known "Force Concept Inventory" (FCI) [10] (see also appendix). The questions are translated in Dutch, the native language of our students, for a better understanding. No feedback is provided at this stage; only the final score is communicated. Before entering the work session, the students have to prepare the physical experiments profoundly. Traditional pre-laboratories are derivations of equations or calculation of the results using sample data. This preparation is elaborated with a test on the physical concepts related to the experiment. The students can answer a few concept questions on Dokeos, the electronic learning platform used at the University College Ghent. The concept questions are presented as multiple choice questions and adequate feedback is provided at the same time as this test is rather for instructing purposes than for testing.

The effectiveness of this method is tested in two ways, looking at the results of the test about the experiments and the results of the reprise of the initial multiple choice test. Correlations between the different scores and comparisons of the scores during the years show the usefulness of the method.

The method is now used for the instructions in the work session of the course Physics I of the master degree in Applied Engineering Sciences. The course Physics I is taught in the 2nd semester (12 weeks) of the 1st Bachelor year during 2 hours a week of theory and 3 hours of a multidisciplinary work session.

3. RESULTS

3.1. Concept test

First the misconceptions are listed using the above described multiple choice test. The test contains 6 different questions about force, gravity and motion. The results are presented in Table 1. The score is presented in % and the standard deviation is indicated. A score of 60% is the threshold for understanding Newtonian mechanics [9], although this comparison is maybe not valid as the full FCI test is not performed. The fraction of maximum possible gain realized, G, is calculated as:

$$G = \frac{S_f - S_i}{100 - S_i} \tag{1}$$

Where S_i and S_f are the pre- and post test score in percent [11].

Pre-test % (St. Dev.)	*Post test % (St. Dev.)*	*G*	*Number of Students N*
51 (23)	65 (25)	0.27	85

TABLE 1. Multiple choice score.

A traditionally taught class gets a G between 0.16 and 0.25 [12], [10] and classes taught more interactively: 0.36 < G < 0.68 [11].

The indicated number of students is those who performed both the pre- and post test. Both tests were filled in voluntary without any consequence on their grades. The pre-test is performed by 113 students, the post test by 171.

From Table 1 can be seen that the score at the pre-test is rather high. Scores at the pre-test of the FCI for the science students at the University Ghent give a value of 40% [5]. At the high schools in United States values between 27% and 42% are found [9]. So the students at the University College Ghent score rather well. The comparison is although not completely valid as our students only took a small part of the FCI test. It should be interesting to investigate how the answers on this selection of questions correlate with the full set of questions. This will be done in the near future.

Another explanation for the higher score can be in the fact that they had already one semester of instruction in higher education. The fraction of maximum possible gain realized is somewhat higher than the normal score for a traditionally taught class. This is an important increase especially taking into account the high score at the pre-test which makes it more difficult to improve.

The scores for the individual answers at the questions are presented in Table 2. The questions are numbered corresponding to the numbering in the FCI (new form from 8/95 [13]) (see also in appendix). The Newtonian concept that appears in the question is also indicated [9].

	Question 1		*Question 4*		*Question 8*		*Question 9*		*Question 13*		*Question 14*	
Answer	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*
A	22%	16%	51%	42%	12%	11%	4%	4%	10%	11%	10%	9%
B	7%	4%	0%	2%	54%*	61%*	13%	11%	21%	6%	5%	6%
C	50%*	60%*	0%	0%	3%	4%	12%	18%	43%	34%	16%	19%
D	19%	19%	0%	1%	14%	12%	5%	2%	27%*	46%*	68%*	66%*
E	1%	1%	49%*	55%*	17%	12%	66%*	66%*	0%	2%	1%	0%
Concept	Gravitational acceleration independent of weight		Third law for impulsive forces		First law no force, second law impulsive force		Vector addition of velocities, second law impulsive force		Superposition cancelling force, passive solid contact, gravitation		Gravitation parabolic trajectory	

TABLE 2. Score for the individual answers at the questions. The correct answer is indicated with a *.

From Table 2 can be seen that there are differences in the scores. But for most questions a majority of the students gets the right answer. Only question 13 gives great difficulties in understanding. This question illustrates one of the classic examples of a persistent misconception: how to describe a simple toss of an object vertically in the air. Answer C is representative of a typical "folk physics" explanation: the hand imparts a force to the object, which drives the object into the air against gravity. The hand force gradually dies away, eventually balancing gravity at the peak of the toss. Other institutions have noticed the same problems with this question (at the University Ghent between 6% and 40% [5] of the students answered correct, in USA between 5% and 14% [9]). Fortunately the score is greatly enhanced in the post-test, but still a majority has a problem with this concept.

3.2. Disciplinary knowledge test

Before entering the work session the students prepare the physical experiments profoundly using the available lab notes. To test whether they understand the physical background of the experiment sufficiently, they can solve some concept questions about the subject that they have handled. In total the students perform 6 experiments with 2 to 4 questions on each subject, 19 concept questions (CQ) in total.

The students were not obliged to fill in the concept questions but were however stimulated to do so for a better understanding. The total population of 1st bachelor students in the course Physics I contains 243 students. From this population 144 students had answered at least one concept question. On an average each question is answered by 115 students or the students answered averaged 15 questions. There can be stated that the major part (70% of the students) who participate in the test answered all the questions. On an average 60% of the questions were answered correctly, this percentage varied however between 23% and 87%.

The score at the disciplinary knowledge test related to the performed experiments is compared with the score at the test of the students the year before. The results are presented in Table 3. The first row presents the results at the test when no extra concept test is provided (without CQ). The second row shows the results when the students could use the concept questions during the preparation of the physical experiments (with CQ). They could not review the concept questions for the preparation of the test. The questions with correct answers were provided on demand but only some 5 students asked for them.

	1st Bachelor	
	Score (St. Dev.)	*Number of students N*
Without CQ	4.6 (1.6)	207
With CQ	5.4 (1.8)	243

TABLE 2. Disciplinary knowledge test score (max 10).

Using the Student's t-test, we can conclude that the scores are statistically different (a α–value of 4 10^{-7} is found), meaning that the students using concept questions gets a better result than the students of the year before. So the performed method has a positive influence on the understanding of the physical concepts. The F-test indicates however a α- value of 5% meaning that the chance that the standard deviation of both populations is the same, is rather poor. So maybe the student populations are not similar. Other influences as differences in the student population, different knowledge level before the test, different test questions, … can be important.

Only about half of the students have answered the concept questions. So this population can be divided in different groups. As a first test we just asked the students to fill in the concept questions. We decided not to reward or punish the students in their grades when they did or didn't answer the concept questions. The follow-up of the results is very time consuming as not all the students perform the same experiments during one work session. It is therefore necessary to implement a better method to follow and enhance the student's participation in the pre-laboratories (see further).

The total population is now further divided according to the frequency that the students answered the concept questions. We divided them in three groups. The first group (prepare always the questions) answered at least 15 of the 19 questions (we 'forgive' them for forgetting once); the second group (prepare sometimes the questions) answered between 5 and 15 questions (so for 2 to 5 experiments), and the third group (prepare no questions) answered less then 4 questions (none or for only 1 experiment). The results for both the test score and the average G are presented in Table 4.

From Table 4 we can conclude that the students who use the concept questions to prepare their experiments gets better results at the test and obtain a better understanding of the concepts itself, compared to the students who don't use them (the t-test using the data of the students who answered always or never gives a α–value of 0.0014). In this case the students had performed the same test and the F-test indicates a great chance (70%) that both populations are comparable. So the observed difference in the score is most likely due to the more profound preparation of the experiments.

	Score (St. Dev.)	*Number of students N*	*G*
Prepare always the questions	5.8 (1.8)	105	0.35
Prepare sometimes the questions	5.8 (1.9)	16	-0.19
Prepare no questions	5.1 (1.8)	122	0.07

TABLE 4. Disciplinary knowledge test score (max 10) depending on the frequency of answering the concept questions.

4. IMPROVEMENTS

One of the problems of the presented method is the low response. Less than half of the students in the first bachelor year fill in the concept questions consequently. So next to improving the method it is important to enhance the participation degree of the students. To motivate students to take part on the 'pre-labs' we consider the method presented by Murphy [14]. The students at the University of Liverpool have to fill in an assignment to earn a password for the lab notes. We will use this method to provide a password to enter the laboratory.

A first improvement will be that we provide also some concept questions for the preparation of the theoretical test. The test is an open book test and students underestimate the difficulty of these test. Mostly they are not well prepared and by providing some questions they would have an idea of their state of physical knowledge.

A further improvement uses the pre-labs combined with relevant concept questions as presented in the JiTT [6] method. In stead of the traditional pre-laboratories it uses physlets (Physics applets) [15]. The disadvantage of the traditional pre-laboratories is that they are mostly graded after the laboratory and there are no observations and analysis required. Using the physlets, the students observe an animation, make measurements using that animation and answer some questions before the beginning of the laboratory. Using an electronic learning platform this leaves room for personal instructions before entering the laboratory.

5. CONCLUSIONS

In the work session physics both disciplinary knowledge is trained by introducing concept questions and attention is paid to the development of competences. The presented pre-labs are a useful tool to enhance the understanding in physical concepts although the system can be improved and needs some time for further evaluations. To ensure that the "new" engineers develop the necessary skills to be both critical and able to solve complicated problems adequately a more multidisciplinary approach is designated with a great emphasize on the relevant disciplinary knowledge.

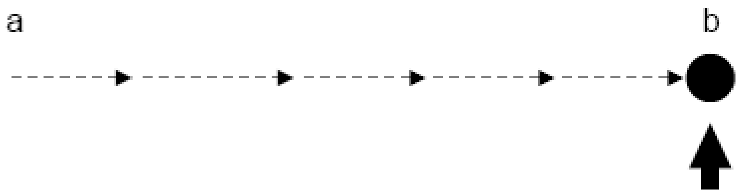
APPENDIX: USED FCI QUESTIONS [13]

1. Two metal balls are the same size but one weights twice as much as the other. The balls are dropped from the roof of a single story building at the same instant of time. The time it takes the balls to reach the ground below will be:
   A. about half as long for the heavier ball as for the lighter one.
   B. about half as long for the lighter ball as for the heavier one.
   C. about the same for both balls.
   D. considerably less for the heavier ball, but not necessarily half as long.
   E. considerably less for the lighter ball, but not necessarily half as long.

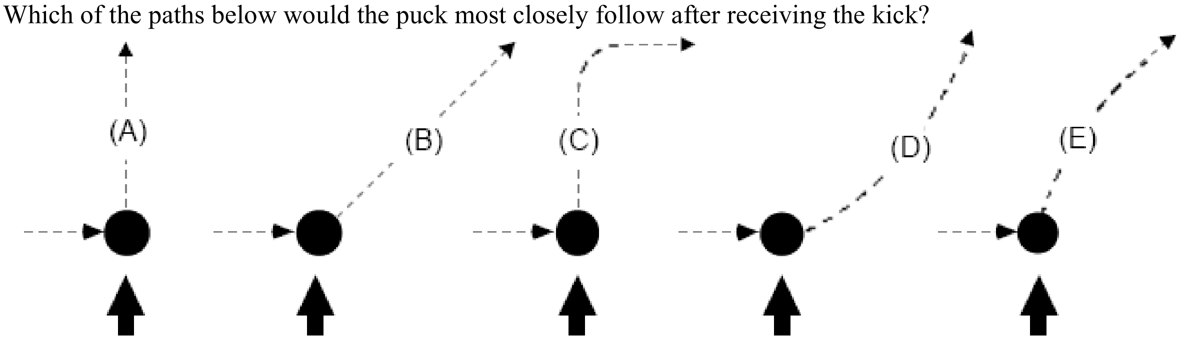
4. A large truck collides head-on with a small compact car. During the collision:
   A. the truck exerts a greater amount of force on the car than the car exerts on the truck.
   B. the car exerts a greater amount of force on the truck than the truck exerts on the car.
   C. neither exerts a force on the other, the car gets smashed simply because it gets in the way of the truck.
   D. the truck exerts a force on the car but the car does not exert a force on the truck.

E. the truck exerts the same amount of force on the car as the car exerts on the truck.

8. The figure depicts a hockey puck sliding with constant speed v_0 in a straight line from point a to point b on a frictionless horizontal surface. Forces exerted by the air are negligible. You are looking down on the puck. When the puck reaches point b, it receives a swift horizontal kick in the direction of the heavy print arrow. Had the puck been at rest at point b, then the kick would have set the puck in horizontal motion with a speed v_k in the direction of the kick.



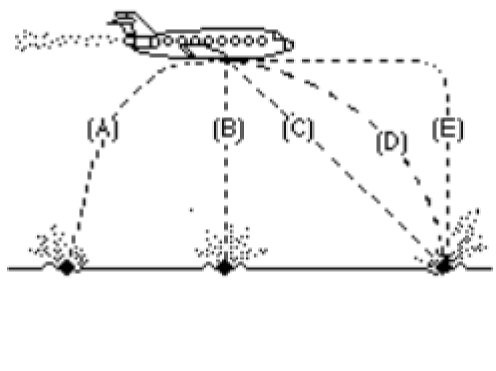
Which of the paths below would the puck most closely follow after receiving the kick?



9. The speed of the puck just after it receives the kick is:
   - A. equal to the speed v_0 it had before it received the kick.
   - B. Equal to the speed v_k resulting from the kick and independent of the speed v_0.
   - C. Equal to the arithmetic sum of the speeds v_0 and v_k.
   - D. Smaller than either of the speeds v_0 or v_k.
   - E. Greater than either of speeds v_0 or v_k, but less than the arithmetic sum of these two speeds.

13. A boy throws a steel ball straight up. Consider the motion of the ball only after it has left the boy's hand but before it touches the ground, and assume that forces exerted by the air are negligible. For these conditions, the force(s) acting on the ball is (are):
   - A. a downward force of gravity along with a steadily decreasing upward force.
   - B. a steadily decreasing upward force from the moment it leaves the boy's hand until it reaches its highest point; on the way down there is a steadily increasing downward force of gravity as the object gets closer to the earth.
   - C. an almost constant downward force of gravity along with an upward force that steadily decreases until the ball reaches its highest point; on the way down there is only a constant downward force of gravity.
   - D. an almost constant downward force of gravity only.
   - E. none of the above. The ball falls back to ground because of its natural tendency to rest on the surface of the earth.

14. A bowling ball accidentally falls out of the cargo bay of an airliner as it flies along in a horizontal direction. As observed by a person standing on the ground and viewing the plane as in the figure at right, which path would the bowling ball most closely follow after leaving the airplane?



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