Introducing Physics Concepts with Illustrative Stories

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Abstract

The algebra based Introductory Physics course is offered to all students majoring in Biology, Chemistry, Computer Science, and Polytechnic Studies in our college. One of the challenges for these students in learning this course is grasping the physics concepts. They have the tendency to reduce learning to memorizing, and fail to concentrate their effort on understanding the theoretical structure and the connections between concepts and reality.

Fortunately, most concepts in this course are closely related to everyday life experience, so they can be introduced with illustrative stories. Specifically, the automobile is an excellent example for many concepts in Newtonian mechanics. Besides, some theories and concepts can also be introduced by experimental demonstrations and simulations. For example, energy conservation can be illustrated by the motion of a pendulum. The interactive simulation in PhET[1] is very helpful, where the kinetic and potential energy levels are demonstrated clearly. In addition, one can slow down the time so that students can see more clearly the transition between these two forms of energy. Furthermore, air friction can be activated and its magnitude is adjustable, in this way the dissipation of energy can be illustrated.

The effectiveness of this approach in teaching Introductory Physics I was assessed with Force Concept Inventory (FCI). At the beginning of the semester, a subset of FCI was tested. At the end of the semester, the complete set of FCI was used in testing, and the gain measured is statistically significant. Following Richard Hake's formula of knowledge gain, the result is G=0.43, far higher than the national average of 0.23 with traditional instruction. On the other hand, a deeper analysis also shows the limitation of the everyday life examples, as air friction makes a big difference at high speed.

Introduction

Scientific knowledge can generally be classified into three categories: factual knowledge, conceptual knowledge, and procedural knowledge.[2] Even primitive tribes have significant amount of knowledge about their living environment, however, it is mainly at the factual knowledge level. On the other hand, factual knowledge, such as experimental data, is the foundation of science. Conceptual knowledge is at a higher level, where a structured system of concepts is constructed and various phenomena are interconnected. Procedural knowledge refers to the methods and approaches in problem solving with such a system of concepts. Therefore, the construction of conceptual knowledge plays the crucial role in science and engineering.

Teaching at the level of factual knowledge is very easy, as rote memory is often sufficient. However, it is rather challenging for students to climb up the steep slope and rise up to the level of conceptual knowledge. A common pitfall for many students is learning physics is equation shopping, and they often become confused when facing problems slightly different from the examples discussed in class. Without the connection to the phenomena in the real world, the physics concepts cannot be fully engaged. Therefore, it is helpful to introduce physics concepts with the background of everyday life. In addition, the physics labs associated with this course are also very beneficial. Unfortunately, many students over concentrate on following the procedures and getting the results during the lab sessions, and they often pay less attention to the concepts and theories behind the experiments.

Concepts and Stories

Unlike in advanced physics courses, many concepts in introductory physics can be related to everyday life experience. Therefore, they can be introduced by tapping into such a vast intuitive knowledge base. Specifically, the automobile is an excellent example for many concepts in Newtonian mechanics.

Acceleration is a concept of crucial importance, which is connected to velocity and force in kinematics and dynamics, respectively. However, this concept is rarely used directly in everyday life, and there is a lack of vocabulary to describe it. In the specifications of automobiles, acceleration is not listed directly; instead, it is described in the acceleration time from 0 to 60 mph. This example reflects the definition of acceleration, which connects the two related parameters: the change of velocity and the time interval. With the unit converted, students can find the acceleration easily from the provided time interval.

The concepts of centripetal acceleration and force are a little challenging for most students, and their driving experience on curved paths is very helpful. At the intersection of two highways, one often needs to make a sharp turn to complete the transfer. Coming to such an intersection, one usually sees a sign of speed limit, which is much lower than the speed limit on the highway. An investigation on how to set the speed limit can lead students to find the relationship among several parameters, such as the radius of the curved path, weather condition related friction coefficient, and banking angle, etc.

Although most students never had the experience of a head-on collision, they are well aware of the danger of such an accident. Therefore, when the principle of linear momentum conservation is introduced with such a situation, students can grasp the idea very easily. If the masses of the two vehicles involved are quite different, students can predict correctly that the lighter vehicle will suffer from a much larger acceleration during the collision. With the knowledge of this conservation law, students can find the relationship between mass and the change of velocity. In addition, mechanical energy conservation can be related to the experience of driving down a steep slope.

Translation is a familiar form of motion, but rotation is a challenge for many students. There are two large dials in the dashboard of most automobiles: one of them shows the speed of the vehicle (speedometer), the other one displays the angular speed of the engine’s crankshaft (tachometer). Most people just pay attention to the former and ignore the latter. A question is raised in class on how a vehicle measures its speed, and the answer comes from the relationship between the linear velocity and angular velocity of the wheels. Since the nominal radius of tires is known, there is a simple relationship between these two parameters. This example is helpful for students to understand the concept of angular velocity, as well as its relationship with linear velocity.

Assessment

At the beginning of the semester, a subset of the Force Concept Inventory (FCI)[3] was used as a pre-test. As we know, the complete FCI has 30 multiple-choice questions and it is ten pages long. Most of the students in this class have never learned any physics before, and thus taking a test with the complete set of FCI questions is a daunting task too challenging for them. Since there was no credit for getting the correct answers in the pre-test, some students might just pick the answers randomly if the full set of FCI was used. In that case, the accuracy of the comparison would become flawed. Therefore, a subset of problems, which can be understood easily, were selected. The problems are on pages (2, 4, 6, 9) of the FCI, and the problem numbers are (5, 6, 7, 12, 13, 14, 17, 18, 25, 26, 27). The number of students who took this test is 111, and the result of pre-test is shown in Table. I.

Table I Pre-Test Result (111 students)

Problem #	**5**	**6**	**7**	**12**	**13**	**14**	**17**	**18**	**25**	**26**	**27**
Correct #	12	67	61	64	4	32	8	11	10	2	56
Correct %	10.8%	60.4%	55.0%	57.7%	3.6%	28.8%	7.2%	9.9%	9.0%	1.8%	50.5%

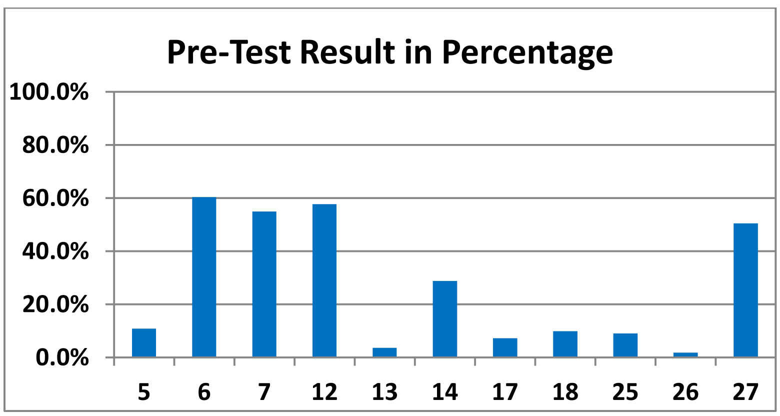

Fig. 1. Percentage of the students with the correct answer in pre-test.

The data in Table I and Fig. 1 shows that four problems (6, 7, 12, 27) are pretty easy, and more than half of students got the correct answer before learning this course. Problems #6 and # 7 are very similar, and they are related to the motion of a particle when the centripetal force disappears suddenly. Problems #12 and #14 are about the trajectory of a horizontal projectile. All these four problems are with illustrations, which are very helpful for students to figure out the correct answers.

Problems #25-27 are with the same background: someone pushes a large box on a horizontal plane with friction. In the case of problem #25, the velocity is constant, so Newton's first law can be applied. In the case of problem #27, the pushing force disappeared, and 50.5% of the students figured out that the box should slow down. However, only 1.8% of students got the correct answer for problem #26, when the pushing force is doubled. Following Newton's second law, there is a constant acceleration since the friction force is unchanged. However, the wording of this option is "with a continuously increasing speed", which sounds unrealistic to the students.

Because only two students got the correct answer for problem #26, we investigated further on the selections: 38 students (34.2%) selected 'A' (double the speed), 44 students (39.6%) selected 'B' (at a slightly higher but constant speed), 8 students (7.2%) selected 'C' and 19 students (17.1%) selected 'D', these last two options have a transient period. Since 74% students selected 'A' or 'B', their intuitive understanding of this problem is that the speed is determined by the pushing force. Actually, this conclusion makes sense when one considers the motion of an automobile or an airplane, because the air resistance is a function of the speed. This shows the limitation of everyday life examples, though they can help students understand the basic concepts.

At the end of the semester, a post-test was conducted with the full set of FCI and the result is shown in Table II and Fig. 2. Among the 30 problems, the correct rates of 16 of them are at or above 50%. On the other hand, 4 problems have correction rate below 25%, but only one of them is below 20%, which is the correct rate of a random guess. Problem #26 remains to be the one with the lowest correct rate at 17.7%, though it is about ten times as high as the pre-test result.

Table II Post-Test Result of Complete FCI (96 students)

Problem #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Correct #	59	29	61	47	21	83	70	54	56	52
Correct %	61.5%	30.2%	63.5%	49.0%	21.9%	86.5%	72.9%	56.3%	58.3%	54.2%
Problem #	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Correct #	22	86	23	50	27	67	44	25	51	43
Correct %	22.9%	89.6%	24.0%	52.1%	28.1%	69.8%	45.8%	26.0%	53.1%	44.8%
Problem #	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Correct #	48	47	40	60	29	17	67	56	68	26
Correct %	50.0%	49.0%	41.7%	62.5%	30.2%	17.7%	69.8%	58.3%	70.8%	27.1%

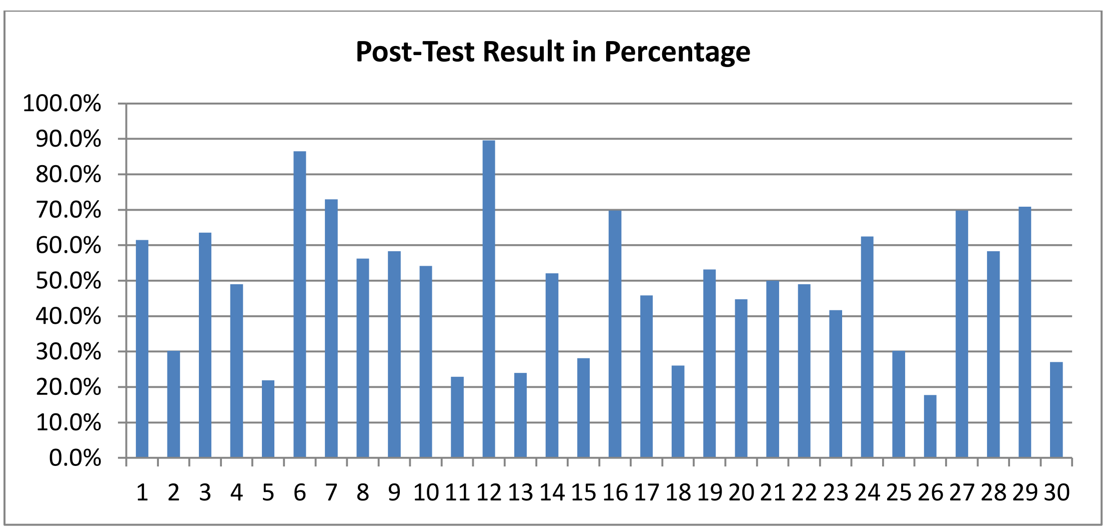

Fig. 2. Percentage of the students with the correct answer in complete FCI post-test .

In order to make a comparison with the pre-test, the data of the same set of problems are sorted out, which is shown in Table III. Besides problem #26, there is also huge increase in correct rate for problem #13 (3.6% → 24.0%) and problem #17 (7.2% → 45.8%). In addition, the data of pre-test and post-test is shown together in Fig. 3. A doubled tailed t-test (paired two samples for means) was conducted with Excel, and the p-value was found at 2.089×10^{-5}. This result indicates that there is significant increase in correct rate for all the problems.

Table III Post-Test Result (96 students)

Problem #	5	6	7	12	13	14	17	18	25	26	27
Correct #	21	83	70	86	23	50	44	25	29	17	67
Correct %	21.9%	86.5%	72.9%	89.6%	24.0%	52.1%	45.8%	26.0%	30.2%	17.7%	69.8%

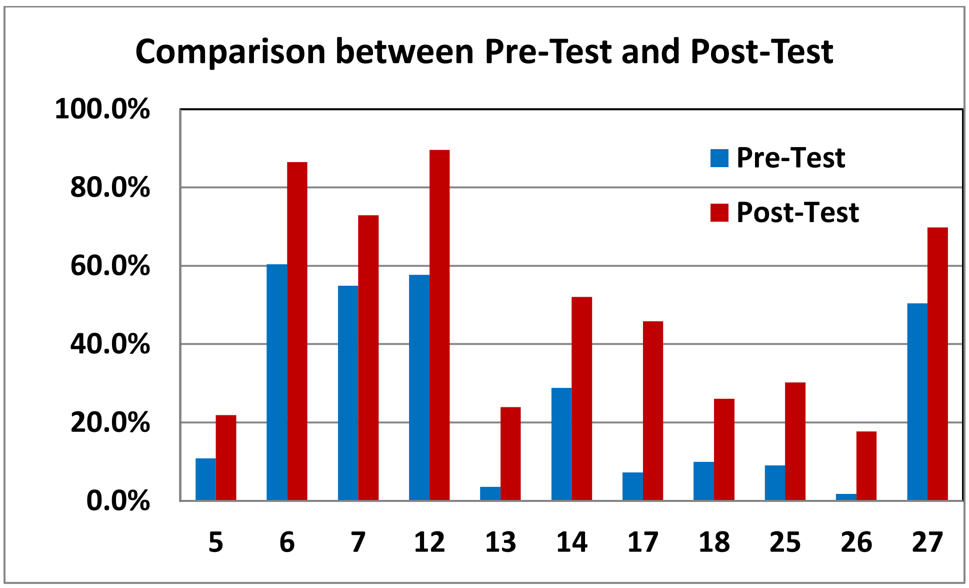

Fig. 3. Comparison of the correct rate in pre-test and post-test.

Richard Hake collected data across the country on student performance on the FCI, and he proposed a formula for knowledge gain to measure the effectiveness of instruction:

$$G = \frac{posttest\ average\% - pretest\ average\%}{100 - posttest\ average\%}$$

With 6000 students in his sample, he found that the gain is at $G = 0.23 \pm 0.04$ for conventional instruction and $G = 0.48 \pm 0.14$ for interactive-engagement instruction.[4] Although questions were often asked during lectures, the style of our teaching belongs to the category of conventional instruction. The data shows that the gain of this course is at $G = 0.43$, which is at a much higher level abreast to that of interactive-engagement instruction. Therefore, it indicates that this approach is rather effective in helping students grasping the physics concepts. In addition, the connection to the driving experience can also attract students' attention, which becomes a serious challenge for courses like this in recent years.

Summary

When physics concepts are introduced with familiar examples, students can understand them more readily. Since driving an automobile is an experience familiar to most of the students, many concepts in this course are introduced from this background, such as the concepts of acceleration, centripetal force and acceleration, linear momentum conservation and mechanical energy conservation, as well as the relationship between linear and rotational motions. Force concept inventory was used in pre-test and post-test, and the results show that this approach is rather effective, and there is a significant gain in understanding at the end of the semester. However, there is also a limitation of everyday life experience, which gives rise to some wrong concepts in Aristotelian physics.

Reference

[1] https://phet.colorado.edu/

[2] Lorin Anderson, David Krathwohl, Peter Airasian, Kathleen Cruikshank, Richard Mayer, Paul Pintrich, James Raths, Merlin Wittrock, *A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives*, Pearson, 2000. ISBN: 978-0321084057.

[3] D. Hestenes, M. Wells, G. Swackhamer, “Force Concept Inventory”, *The Physics Teacher*, vol. 30, pp. 141-158, 1992.

[4] R. R. Hake, “Interactive-engagement vs traditional methods: A six-thousand student survey of mechanics test data for introductory physics course,” *Am. J. Phys*. vol. 66, pp. 64-74, 1998.