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Newton's Third Law of Motion: Elusive Even Among Graduate Engineering Students

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Newton's Third Law of Motion: Elusive Even Amongst Graduate Engineering Students

Some Fundamental Laws of Physics remain elusive even to graduate engineering students, as they cannot understand them well enough to apply them correctly to most situations. Newton's 3rd Law of Motion is one of them, as this present study shows. The "Force Concept Inventory" (FCI) questionnaire was given to graduate engineering students as a pre-assessment at the beginning of the "Scientific Foundations of Engineering" course, which is part of the Gordon Engineering Leadership program and aspires to deepen the understanding of the fundamental laws of science that underlie all engineering disciplines. Two weeks after the students participated in a 2.5-hour session on reviewing classical mechanics, part of which focused on the conceptual understanding of Newton's Laws of Motion, especially the third Law, the same questionnaire was given to them as post-assessment and the results, including the correct answers, were discuss after the post-test. The students showed remarkable improvement. The results of this study and the pedagogical approach used, which the author has developed over a number of years as part of Professional Development courses for Middle and High School STEM Teachers, will be presented and discussed. This approach is consistent with the research findings on *How People Learn.*

Although it is encouraging to see such a great improvement in the students' understanding of the laws of motion after only a couple of hours of interactive teaching, what is of even greater interest is to see if the teaching approach that was used was adequate to reverse the students' misconceptions regarding Newton's Laws of Motion, especially the 3rd Law, permanently or if with time the students fall back to their pre-conceptions. A delayed post-assessment using the same FCI questionnaire was administered to the same graduate students six months later completely unexpectedly and without any prior notice that such an assessment would be conducted. The results, which are presented, analyzed and discussed in the paper, strongly indicate that the teaching methodology used results in reversal of misconceptions that lasts at least six months, suggesting that this change may be permanent.

Introduction

We grow up with many first hand experiences with motion. Everything around us constantly moves and from an early age we try to make sense of how it all works. Unfortunately, as it is well-known, the Laws of motion are completely counterintuitive, which is the reason that many great minds (Aristotle, Archimedes, Galileo and even Newton in the beginning) had all these wrong! As a matter of fact, the way nature works is exactly the opposite from what our "common sense" tells us. It is hard to understand that an object will move in a straight line for ever without a force acting on it, because from our experience we "know" that everything that moves eventually comes to a stop, so we need to keep applying a force in order for it to move with a constant speed! Of course, the role, even the existence, of friction is not obvious. It is, therefore, no surprise that all of us get these laws wrong until we take physics in school. But, as experience and research on "How people Learn" shows, it is not easy to change someone's mind. Therefore, despite the fact that we study these laws, known as Newton's laws of Motion, for many years, students fall back to their intuitive (Aristotelian) understanding of them.

This year, the author started teaching a somewhat unique course called "Scientific Foundations of Engineering," to graduate engineering students with at least three years of work experience who are enrolled in The Gordon Engineering Leadership Program at Northeastern University. This course aspires to teach students the fundamental scientific Principles that underlie all engineering disciplines. The author of this article is the co-author of the book whose title is the same as the name as the course and which was published by Cambridge University Press in August of 2015. This course is part of the Gordon Engineering Leadership Program at Northeastern University. The Gordon Engineering Leadership Program, the last year recipient of the National Academy of Engineering Gordon Prize for innovation in engineering education, has the goal of fostering the development of engineers who have the rare and highly-prized ability to lead an engineering project all the way from concept to a marketable product.

This lack of depth of understanding of fundamental scientific principles and lack of any formal instruction in the science of quantum systems is what was intended for the "Scientific Foundations of Engineering" course in the Gordon Engineering Leadership Program at Northeastern University to address. But before going to Quantum Physics, we start with a quick review of classical mechanics.

Based on his more than 25 years of experience with K-12 science teacher professional development and his knowledge of how to teach through preconceptions, the author decided to give the 1992 version of the FCI[1] to the 34 students in his class of graduate engineering students in order to accomplish three goals:

1. Assess student prior knowledge by probing the level of understanding of these simple fundamental concepts in classical mechanics, especially Newton's Laws of Motions (the 3rd one in particular), by giving the FCI as a pretest;
2. Measure the effectiveness of the teaching method the author has developed over the more than 25 years of experience with designing and conducting professional development courses for hundreds of Middle and High School Science teachers, especially test his approach to teach Newton's 3rd Law, by giving the FCI as a posttest two weeks after finishing the mechanics review, at which point the results and the answers were discussed, and, finally and more importantly,
3. Study the permanency of the correct understanding of Newton's Laws of Motion, especially, Newton's 3rd Law, which seems the most elusive of the three, by giving the same FCI questionnaire as an unexpected and unannounced delayed posttest to the same group of students six months later.

Although the FCI questionnaire has been given to many groups of students[1] throughout the years, and has been used to probe and correct misconceptions in mechanics (Kinematics and Dynamics), as far as the author knows, no one used it to study the effectiveness of a particular teaching approach on reversing permanently the student misconceptions, which linger on even amongst graduate engineering students, despite all the physics they have had throughout their schooling. It was the hypothesis of the author that his approach will have a permanent effect on the students' correct understanding of Newton's Laws of Motion, especially Newton's 3rd. Until now, the method had been proven very effective in the short run. Now, for the first time, based on the data from the six month delayed posttest, the method seems to be effective also in the long run. Table 3 shows students' understanding of each of Newton's Laws of Motion as measured by the subset of the FCI questions (Table 2) that assess each one of them.

Teaching Methodology

The students are confronted with the misconception through questions that assess prior knowledge, followed by probing critical thinking questions that, when answered incorrectly, lead to irrational or contradictory answers. An example of that is the famous "horse and cart" problem or a statement "if the action-reaction pair is equal and opposite, why don't the two forces cancel each other?" Incorrect answers, of course, leading to the absurd conclusion that it is impossible to accelerate (i.e., stop & go). Another case is whether Newton's 3rd law applies when an object is accelerating, probably the most difficult case for a novice to comprehend. Through Socratic dialogue with questions that increase in complexity in a systematic fashion and some simple interactive demonstrations, the students are forced to confront their preconceptions and through active learning[2,3], utilizing peer learning[4] techniques (they have to explain different probing questions to each other after they first think about them on their own – think, pair, share – before we discuss them as a class) they slowly change their understanding and replace their preconceptions (Aristotelian way of thinking) with the coherent Newtonian model of motion.

Data, Analysis and Results

The pretest, posttest and delayed posttest scores for the whole FCI test for all 34 students who took all three tests are shown in Table 1 and in the scattered plots shown in Figures 1 & 2. The scatter plots in Figures 2 and 3 compare the pre-test scores on each question with the corresponding scores in the posttest and the delayed posttest. As Figures 1, 2 & 3 show, with the exception of very few questions, the students did substantially better in most questions in the immediate posttest and, even slightly better in the delayed posttest! (It should be noted that question #15, not one probing understanding of Newton's laws, yields low scores consistently, not because of a conceptual misunderstanding but rather due to the use of esoteric language that confuses the non-experts. The author of this paper has given this questionnaire to many hundreds of teachers and other science and engineering professionals. Most have found the language in this question to be misleading and the vast majority of them usually misinterprets it.) Furthermore, as shown on the last row in Table 3, the average scores for the overall test were raised from 63.4% to 80.2%, in the posttest, given a couple of weeks later, to 82.6% in the delayed posttest, given six months later! These yield 46% *percent of potential gain* [= (posttest – pretest)/(100% - pretest)] for the posttest and even larger, 49%, for the delayed posttest. These indicate that the overall teaching approach is effective and the students have learned the concepts well. But what if we were to examine the questions that pertain to Newton's three laws of motion?

If one looks at the subset of questions that probe each of Newton's Law separately (Table 2 shows which FCI Questions pertain to each Law of Motion[1], it is clear that, before the instruction, the students had the greatest difficulty understanding and applying Newton's 3rd Law of motion, which is by far the hardest to grasp conceptually. As a matter of fact, the pre-test average on Question 13, which had to do with the forces between a small car pushing and accelerating a large car, was only 18%! At the same time, it is interesting to see that this is where the students exhibited their highest gains: from 47.1% (pre-test) to 93.6% (post-test), which is

88% of their percent gain potential(!) to fall slightly to 87.5% (see Table 3 and Figures 1-4), which is better than their score to questions probing understanding of the First and Second Laws. This is most satisfying, as the focus of the teaching was to address mostly misconceptions on the 3rd Law. By all accounts, the data indicates that the misconceptions were addressed effectively and possibly were reversed permanently or at least for six months. The results also reveal that more attention needs to be paid to the other two Laws, with which I had assumed that graduate students would not have much difficulty. The scores on first Law went from 72% in the pre-test to 80% (52% of potential gain) in the posttest to 85% in the delayed posttest and for the 2nd Law from 68% to 76% (24% of potential gain) in the post test to 81% in the delayed posttest.

One may argue that a bias was introduced by discussing the answers after the first posttest, but the author considers this to be minimal, as 1) it is hard for anyone to remember answers to a Multiple Choice test six months later; 2) the students never expected to take this test again; 3) the delayed posttest was conducted without prior notice; and 4) the last column in Table 1 supports this assumption, as it shows that in a some questions the was a significant drop between the post- and delayed post-test. In any case, the author plans to investigate this effect in the future.

The finding that the 3rd Law is the one with which the students have more difficulty is consistent with the finding of Hestenes et.al[1]. and of the author of this paper, who has given this pre/posttest to hundreds of teachers, who have participated in the professional development programs over more than 20 years, and retired science and engineering professionals who have participated in the RE-SEED Program. (RE-SEED – www.reseed.neu.edu – recruits, trains, and places retired science and engineering professionals in STEM classrooms to support teachers and students as volunteers. Since 1991, the program trained more than 800 volunteers who have offered more than 850,000 hours of their time working with more than 125,000 in 14 different US states, most of them in MA.)

Conclusions

The results from the pretest, posttest and delayed posttest show that

1. common misconceptions of Newton's Laws, especially Newton's 3rd Law, known to be the most difficult of them conceptually, which exist amongst middle school, high school and college students, as well as K-12 science teachers (author's 25-year personal experience with professional development courses), also exist amongst graduate engineering students
2. the methodology used by the author is yielding impressive
    a. changes in the understanding all Newton's Laws of motion, especially in the most elusive one, Newton's 3rd Law, in the short run, something that others[1,5] have also shown; and
    b. retention of these conceptual understandings even six months later, strongly suggesting that the reversal of common misconceptions on Newton's Laws may be permanent.

Finally, it is encouraging to see that with appropriate focused interactive teaching we can turn students from Aristotelian into Newtonian thinkers when it comes to understanding the laws of motion. It would be great to be able to administer this test to the same students in couple of years from now to confirm that the change is indeed permanent.

Table 1. Percent Pre, Post and Delayed Posttest scores and differences between them

	% FCI Scores for Each Question			Differences between the test scores		
Question #	**Pretest**	**Posttest**	**Delayed Posttest**	**Post - Pre**	**Delayed Post - Pre**	**Delayed Post - Post**
1	79.4	94.1	97	14.7	17.6	2.9
2	41.2	94.1	94.1	52.9	52.9	0
3	55.9	67.6	75.6	11.7	19.7	8
4	85.3	76.5	97.1	-8.8	11.8	20.6
5	58.8	85.3	84.8	26.5	26	-0.5
6	76.5	85.3	87.9	8.8	11.4	2.6
7	64.7	70.6	79.4	5.9	14.7	8.8
8	79.4	94.1	91.2	14.7	11.8	-2.9
9	58.8	88.2	94.1	29.4	35.3	5.9
10	85.3	82.4	97.1	-2.9	11.8	14.7
11	52.9	91.2	97.1	38.3	44.2	5.9
12	73.5	88.2	79.4	14.7	5.9	-8.8
13	17.6	88.2	58.8	70.6	41.2	-29.4
14	79.4	94.1	100	14.7	20.6	5.9
15	29.4	8.8	38.2	-20.6	8.8	29.4
16	73.5	79.4	88.2	5.9	14.7	8.8
17	73.5	73.5	79.4	0	5.9	5.9
18	61.8	82.4	76.47	20.6	14.67	-5.93
19	97	88.2	94.1	-8.8	-2.9	5.9
20	73.5	85.3	94.1	11.8	20.6	8.8
21	79.4	85.3	67.6	5.9	-11.8	-17.7
22	58.8	82.4	91.2	23.6	32.4	8.8
23	64.7	79.4	73.53	14.7	8.83	-5.87
24	52.9	64.7	67.6	11.8	14.7	2.9
25	79.4	82.4	88.2	3	8.8	5.8
26	61.8	85.3	73.53	23.5	11.73	-11.77
27	76.5	94.1	91.2	17.6	14.7	-2.9
28	52.9	73.5	61.8	20.6	8.9	-11.7
29	76.5	70.6	73.53	-5.9	-2.97	2.93

Figure 1. Pre (**blue**), Post (**red**) and Delayed (**gray**) Post-test scores for each FCI question

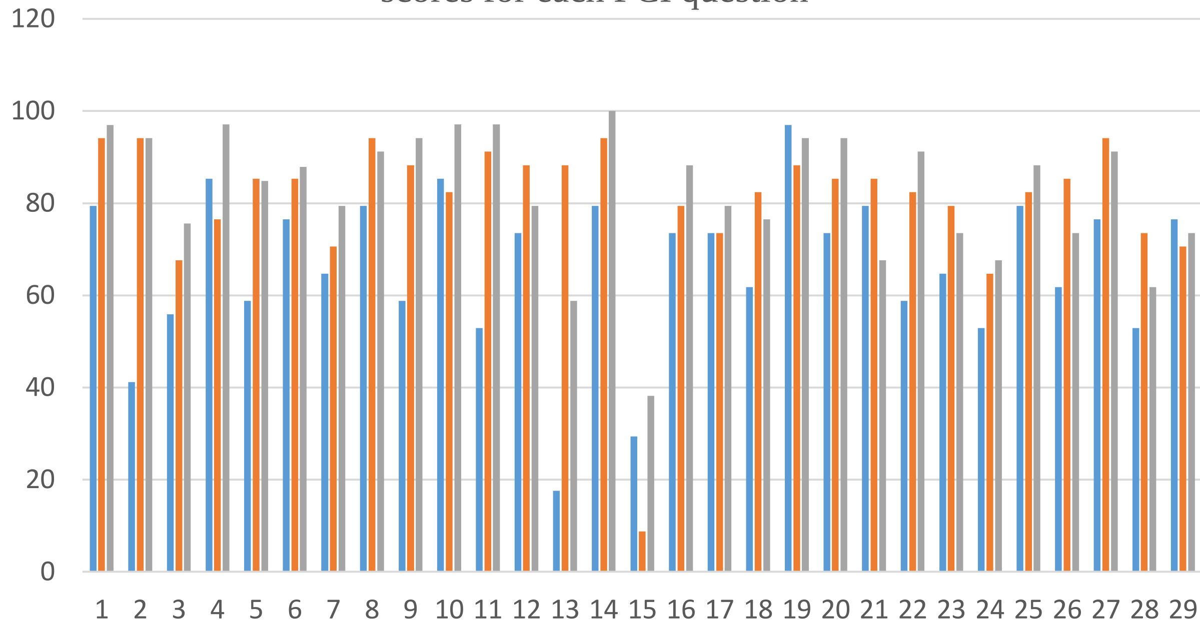

Table 2. FCI Questions that pertain to Newton's Three Laws of Motion			
	Newton's 1st Law	**Newton's 2nd Law**	**Newton's 3rd Law**
FCI Questions	4, 6, 8, 10, 18, 26, 27, 28	6, 7, 24, 25	2, 11, 13, 14

Table 3. Student performance on each of Newton's Laws and FCI as a whole					
Newton's Laws of Motion	**Pre-test**	**Post-test**	**Delayed Posttest**	**Gain as % of Potential (pre vs. post test results)**	**Gain as % of Potential Pre vs. Delayed post-test)**
1st Law	71.8%	85.0%	85.3%	47%	48%
2nd Law	67.9%	75.7%	80.9%	24%	41%
3rd Law	47.1%	93.6%	87.5%	88%	76%
Whole FCI	63.4%	80.4%	82.6%	46%	49%

Figure 2. Pre (horizontal) vs. Post (Vertical) test Scores for Each FCI Question

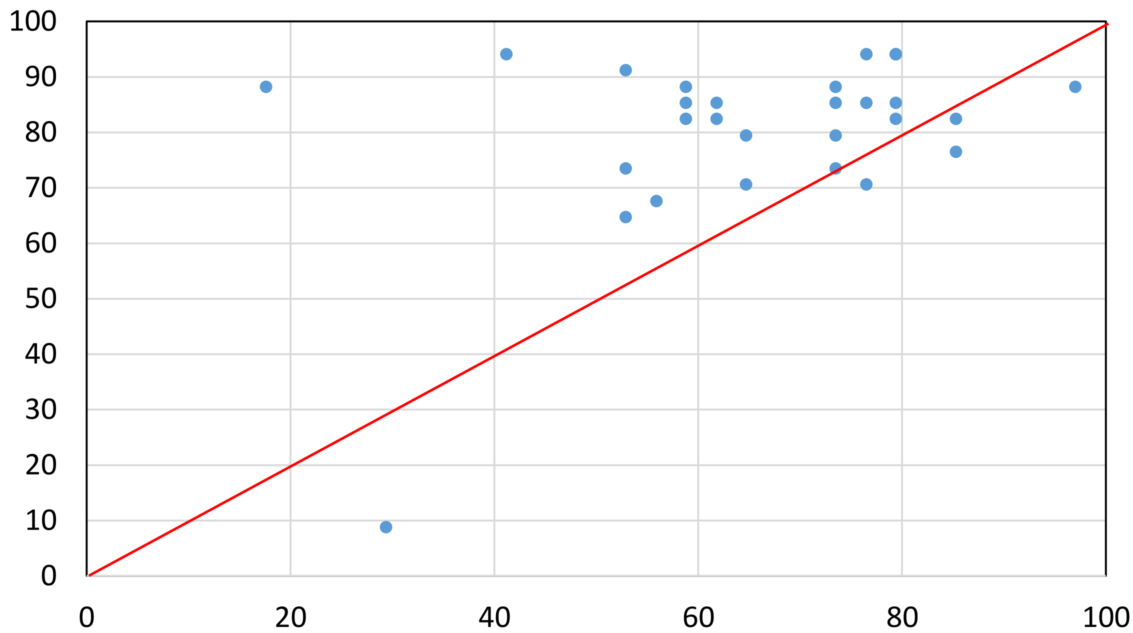

Figure 3. Pre (horizontal) vs. Delayed Post (vertical)test Scores for each FCI Question

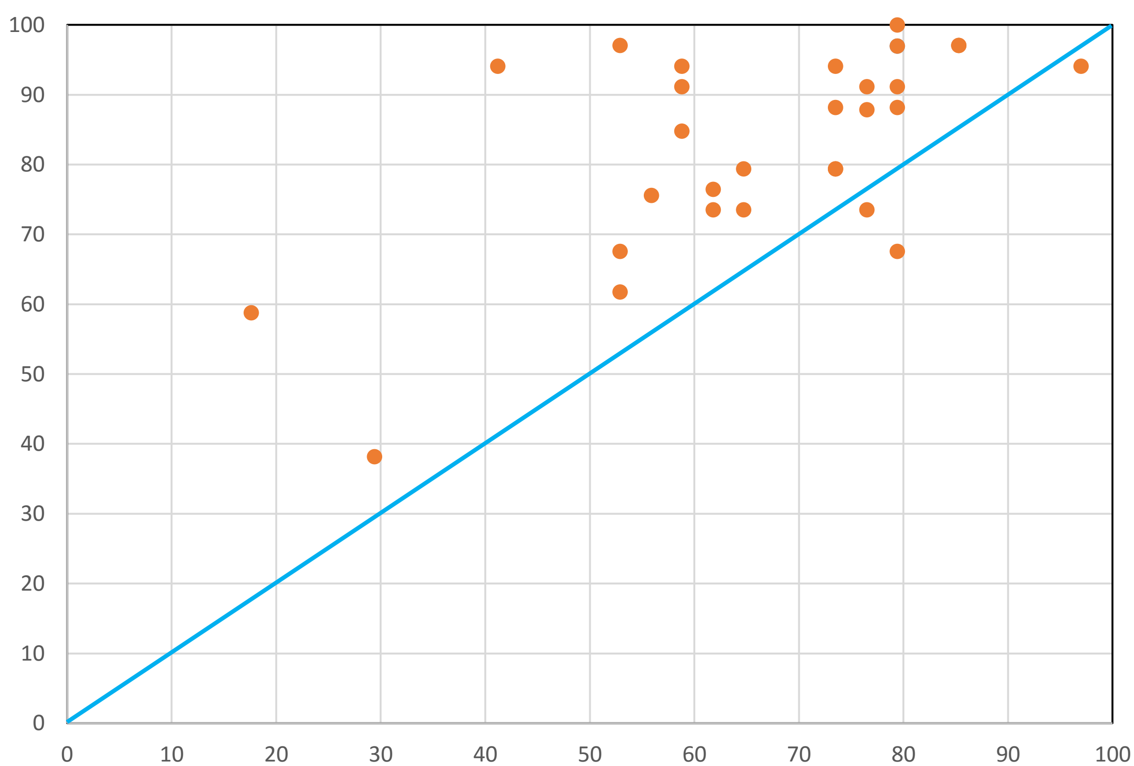

Figure 4. Pre (blue), Post (orange), Delayed Post (gray) Test Results on Newton's Laws and the FCI Test as a whole