

# Fluctuations in Student Understanding of Newton’s 3rd Law

Jessica W. Clark\*, Eleanor C. Sayre<sup>†</sup> and Scott V. Franklin\*\*

\**Department of Physics and Astronomy, University of Maine, Orono, ME 04469*

<sup>†</sup>*Wabash College, Crawfordsville, IN 47933*

\*\**Department of Physics, Rochester Institute of Technology, Rochester, NY 14623*

**Abstract.** We present data from a between-student study on student response to questions on Newton’s Third Law given throughout the academic year. The study, conducted at Rochester Institute of Technology, involved students from the first and third of a three-quarter sequence. Construction of a response curve reveals subtle dynamics in student learning not captured by simple pre/post testing. We find a significant positive effect from direct instruction, peaking at the end of instruction on forces, that diminishes by the end of the quarter. Two quarters later, in physics III, a significant dip in correct response occurs when instruction changes from the vector quantities of electric forces and fields to the scalar quantity of electric potential. Student response rebounds to its initial values, however, once instruction returns to the vector-based topics involving magnetic fields.

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## INTRODUCTION

Pre/post testing of students is virtually the standard for assessing learning in physics [1]. Thornton and Sokoloff [2] used the method to establish the validity of the FMCE and demonstrate the efficacy of active engagement classrooms, a study reproduced on a much larger scale by Hake [3]. Pre/post testing fails, however, to reveal the rich dynamism of student learning. Research on forgetting and interference [4, 5, 6, 7] shows that learning is very subtle, and often time-dependent, with even significant gains sometimes short lived. Sayre and Heckler have applied the between-student method [8] to physics classes. In this method, data are collected regularly through the academic term with comparison between different groups of students. While this requires significantly larger student populations — and overhead on grouping — when successful it allows for a much more detailed picture of student understanding before, during, and after instruction.

## METHODS

### Population

RIT is classified [9] as a large four-year, private university with high undergraduate enrollment, balanced arts & sciences/professions, and some graduate coexistence. At the time of this study, the academic year was divided into four 10-week quarters (including the summer term). Each year  $\approx 2000$  students take introductory calculus based physics, which is offered in a workshop for-

**TABLE 1.** Study population for fall and winter divided by course. In fall, the primary course is physics III and in winter, the primary course is physics I.

|             | Fall      |     |  | Winter    |     | Total |
|-------------|-----------|-----|--|-----------|-----|-------|
| Course      | # of Sec. | N   |  | # of Sec. | N   | N     |
| Physics I   | 5         | 142 |  | 14        | 441 | 583   |
| Physics III | 8         | 257 |  | 5         | 144 | 401   |

mat that integrates lecture, experiment, and short group activities. Adapted after the SCALE-UP project [10], the classes meet for three 2-hour sessions each week, with students seated at tables of six and working in small groups. Classrooms accommodate up to forty-two students, with enrollment in each section varying.

Students are initially sorted into two different tracks based on an Institute math placement exam. Students who fail to achieve a minimum score on this exam are placed into slower-paced calculus and physics sequences. These students meet for four 2-hour workshop meetings (instead of three). In order to ensure that the same material is covered in the regular and remedial sequences, a mid-term and final exam are common across all sections. These comprise 60% of the students’ final grades. Students who achieve an A in the remedial sequence may enroll in the mainstream sequence for subsequent quarters. All students are “mainstreamed” by the third quarter for Electricity and Magnetism. In E&M, there are three tests and a final. All tests are common across sections, with the final all multiple choice. Multiple sections of Mechanics and E&M are offered every quarter, with most students beginning the sequence in the

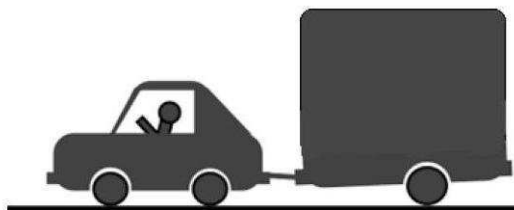
Winter of their freshman year.

Our study tested students in the first (Mechanics) and third (E&M) quarters during the fall and winter quarters of the 2009-2010 academic year. In the fall there were 5 sections of Mechanics (three mainstream ( $N = 109$ ) and two remedial ( $N = 33$ )) and eight sections of E&M ( $N = 257$ ). In the winter, there were fourteen sections of Mechanics (eight mainstream ( $N = 281$ ) and six remedial ( $N = 160$ )), and five sections of E&M ( $N = 144$ ). We found little significant difference between mainstream and remedial sections on the questions involved in this study; henceforth we group the two together for improved statistics. Engineering students dominate the population, comprising 57-83% of the students in Mechanics and 65-83% of E&M students. Participation for each quarter is summarized in Table 1.

## Between Student Testing

RIT's system of multiple sections makes it ideal for a between-student study. First used in physics by Sayre and Heckler [8], this method gives short conceptual quizzes to different sub-groups of the population in successive weeks. This avoids test-retest effects that would occur if the same group took the quiz twice. Different sections are therefore different groups, with section I (for example) completing the relevant quiz in week 3 and section II taking the quiz in week 8. For this type of analysis to be valid, the groups must be approximately normally distributed and have the same variance, which we have confirmed. The order in which each section took a quiz was randomly assigned, and all quizzes were administered at the beginning of class, once per week, in paper format. Students had five-ten minutes to complete each task, which were sometimes appended to an instructor-generated quiz.

Because sections are statistically independent, we can compare the performance of different sections across weeks, essentially capturing student understanding on a weekly time scale. A time plot of average performance, termed the *response curve*, is sensitive to the particulars of the week—the current topic of instruction and coincidence with exams or homework. The conventional pre/post test corresponds to the first and last points on the curve, and can miss much of the dynamic evolution of understanding. Error bars on the response curve are determined using a binomial distribution, and we collapsed data across the fall and winter quarters (by week) to increase sample size. Because the syllabus is unchanged, this is appropriate. Students in, for example, Week 3 in the Winter see the same activities, labs, and lectures as those in Week 3 in the Fall.



- A. The trailer pulls on the car a lot, but the car doesn't pull on the trailer.
- B. The trailer pulls on the car more than the car pulls back on the trailer, but the car still pulls on the trailer.
- C. The trailer pulls on the car exactly as much as the car pulls on the trailer.
- D. The car pulls on the trailer more than the trailer pulls on the car, but the trailer still pulls on the car.
- E. The car pulls on the trailer a lot, but the trailer doesn't pull on the car.

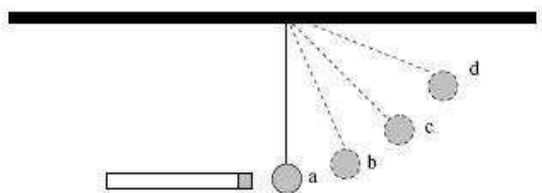
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**FIGURE 1.** Prompt and responses for Newton's Third Law task for mechanics. The students were asked to consider situations where the car was speeding up, constant speed up a hill, constant speed a level road, and slowing down.

## Tasks

Tasks were devised to probe student understanding of Newton's Third Law. In order to align with the instruction of the different classes, tasks were couched in appropriately different contexts. (This also made it easier for us to gain access to E&M sections, as instructors could more easily justify inclusion of the task.) In Mechanics, the task involved a car pulling a trailer (see Fig. 1). Students are asked to compare the forces acting on the car and trailer as the car speeds up, travels at constant speed up a hill, travels at constant speed on a level road, and slows down. The answer choices for each question were the same and the students could select each answer as many times as they wanted.

For E&M, the task was re-written to involve electric charges (see Fig. 2). Students compared the forces acting on the rod and ball as the ball starts to move, speeds up, and slows down as it swings away from the rod and finally when it comes to rest. This question is not completely isomorphic to the Mechanics formulation, and so we do not directly compare the Mechanics and E&M responses. Rather, we look for changes in the response over the course of each quarter, and similarities in how this behavior corresponds to the topic of instruction.



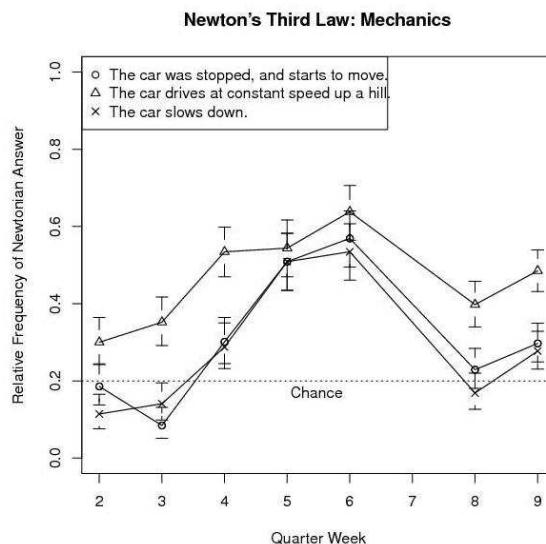
- A. The rod pushes on the ball a lot, but the ball doesn't push on the rod.
- B. The rod pushes on the ball more than the ball pushes back on the rod, but the ball still pushes on the rod.
- C. The rod pushes on the ball exactly as much as the ball pushes on the rod.
- D. The ball pushes on the rod more than the rod pushes on the ball, but the rod still pushes on the ball.
- E. The ball pushes on the rod a lot, but the rod doesn't push on the ball.

**FIGURE 2.** Prompt and response for Newton's Third Law task for physics III. The students were asked to compare the forces on the rod and ball ball started to move, sped up, slowed down and at rest at the apex of the swing.

## RESULTS

### Instruction's positive impact

Figure 3 shows the response curve for students in the Mechanics course. (As noted above, responses are averaged across all sections in both Fall and Winter. A common assessment on an unrelated topic was given to all sections in Week 7, so that data point does not exist.) Shown are average response for the three non-trivial questions; the question involving the car traveling at constant speed on level ground shows a ceiling effect where almost all students answer correctly independent of week, instructor, or any other variable. Although 80% of students have had physics prior to the introductory course at RIT, response during the first few weeks of the course, before explicit instruction of forces or Newton's Laws, hovers around the chance line of 20%. Instruction on forces begins in week 4, and student performance begins to rise, culminating with a maximum performance in week 6. Not coincidentally, week 6 is also the last week of instruction on forces, and includes the examination. After instruction, the response rapidly drops, with two of the questions ending just above the chance line at the end of the quarter. The small dip in week 8 may be due to instructor effect, but without data from Week 7, we are unable to definitively identify a source for the lower score. The low score does not, however, negate the overall result of rise and fall throughout the quarter.

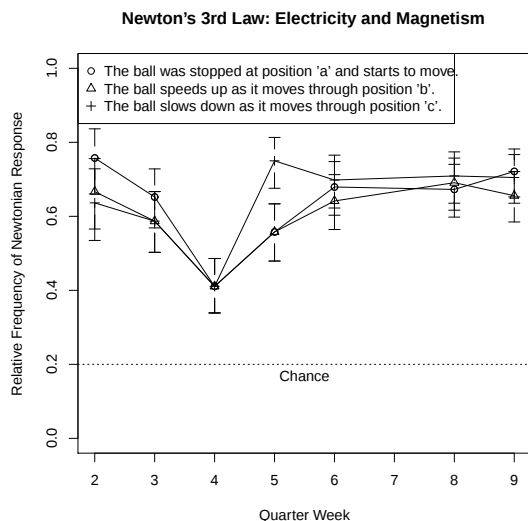


**FIGURE 3.** Response curve for physics I. Before instruction response could be chance. There is a broad peak during instruction with a maximum during week six which is the end of the section on forces.

### Instruction's negative impact

Figure 4 shows the response curve for all students in the E&M course, the question involving the ball at rest having been omitted due to the presence of a ceiling effect. At RIT, E&M is typically taken in the Fall quarter. This means that because of the summer break, it has been approximately 5 months since these students last saw instruction on forces and Newton's laws. (The Spring quarter deals with rotational motion, waves, and miscellaneous physics topics). Nevertheless, students enter with an initial response of 66%, significantly higher than they exited Mechanics. This has two potential explanations. Most likely is a winnowing effect, with the weakest students leaving the sequence before reaching E&M. Failure rates (defined as obtaining a D, F, or withdrawing) in Mechanics average around 25%, and an additional  $\approx 17\%$  exit between Mechanics and E&M. Therefore, students entering E&M are the top 62% of the students in Mechanics, and a higher performance is expected. Less likely is the possibility that instruction in the intermediate quarter has bolstered student understanding. Subsequent testing in this course will take place next year to test this possibility.

The most significant feature of Fig. 4 is the pronounced dip in week 4 to 41%. This drop, 25% points below the average, cannot be explained by instructor or section variance, and so we assert that course topic is the most likely cause. In E&M, the first three weeks are spent on electric fields, Coulomb's Law, and Gauss' law. Week 4 shifts the topic from vector-based concepts to the scalar



**FIGURE 4.** Response curve for physics III. The response is mostly flat around the average of 66 percent with a measurable dip during week 4. This dip corresponds to the period of instruction in electric potential.

topics of electric potential and voltage. We speculate, therefore, that instruction on the scalar electric concepts interferes with response to a vector-based (Coulombic force) question. In week 5 instruction shifts to current, resistance, and circuits. While this is also scalar-based, and we note that the week 5 performance is still below average, we suspect that because instruction is not explicitly involving electric charges the interference effect is lessened.

## CONCLUSIONS

It has been established [8] that student understanding is dynamic, and time-dependent. In this study we have shown that this dynamism continues far beyond the immediate period surrounding instruction. Student response to questions on vector-based topics, like Newton's Third Law, are sensitive to *any* physics instruction they are receiving at the time. "Dissonant" instruction, e.g. topics that emphasize a scalar concept, suppresses student scores. It is fortunate that this interference disappears when instruction returns to more "consistent", i.e. vector-based, topics. We would expect a similar interference effect to occur in the Mechanics quarter during instruction on the scalar topics of Energy. Unfortunately that occurs during Weeks 7 and 8; we have no data for Week 7 (due to a common assessment) and so we are unable to determine if the low score in Week 8 is an instructor effect or interference. Future work is looking into this

question.

The impact of current instruction on previously learned knowledge has been loosely termed "interference". [7] It underscores the complexity of student learning, as students struggle to identify, activate, and use appropriate knowledge in response to a prompt. Even strong students, who have already progressed through two previous quarters of physics and show a high initial score, struggle to reconcile a strange prompt with their current frame of mind. The implications for testing and assessment may be profound, calling into question the accuracy of any single evaluation. It broadens the range of contexts that are known to affect student performance (both positively and negatively), and therefore cautions instructors from reading too much into any single assessment. Subsequent research will look at interference effects in strong and weak students, mainstream and remedial sections, and in more explicit vector tasks.

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