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Abstract

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Keywords

Introductory science course, Development of abstract reasoning, Teaching physics

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Abstract
Classical physics has a long history of using demonstrations and experiments to develop ideas in introductory courses. The purpose of this exploration is to examine the effectiveness of a desk-top activity for helping students develop abstract reasoning. In the pilot exploration, students in three laboratory sections of a single physics course were given different supplemental instructions on development of free body diagrams: standard instruction, system schemas, and a new approach building physical models of those schemas. Students using the physical models avoided common errors made by the other two groups. More importantly, their discussion with a student researcher about developing diagrams showed a deeper understanding of the concepts and less guessing than responses of the control groups. In a subsequent use of this activity with an entire class, similar positive results were found for free body diagrams although the activity did not have an impact on related topics in the course.

Introduction

Context

The field of physics has a rich history of using demonstrations and activities to illustrate and develop physics concepts. Books such as *String and Sticky Tape Experiments* (Edge, 1987) have provided instructors with a variety of low cost explorations that are suitable, in some cases, for classroom as well as laboratory use. In the late 1980's, Physics Education Research (PER) groups began to strengthen what has since become a growing field. Research at the University of Washington and Dickinson College focused on development and subsequent testing of activity-based physics instruction. Explorations into the learning benefits for students receiving such instruction (e.g. Thacker, et al. 1994) provide strong support for the effectiveness of an active approach. PER is now at the stage where a series of activity-based introductory text books and workbooks, including *Matter and Interactions* (Chabay & Sherwood, 2002), *Workshop Physics Activity Guide* (Laws, 1997), and *ActivPhysics* (Van Heuvelen, 1997), have become available for use.

Resource issues (including staffing, class size, and facilities) present barriers to implementation of fully activity-based physics in many cases. Additional work has been done to develop activities and exercises for use in more traditional physics courses to

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engage students around difficult concepts or areas of known misconceptions. *Matter and Interactions* (Chabay & Sherwood, 2002) is one active text that is adaptable to a variety of course structures. In another approach, McDermott et al. (2002) have introduced workbooks intended for use in recitation sections of large enrollment physics courses. However, additional approaches to active learning in traditional physics course are still needed, especially for first semester material.

One particular challenge, and one that is shared with instructors in other disciplines, is development of instructions to aid students in the process of building abstract representations of real world problems. Newtonian physics has an advantage in this process in that there is a strong concrete element to the problems on which to build, and the literature and oral tradition suggest many activities to help students with the concrete aspects of the field. This can provide a foundation, both of knowledge and of approach, on which to build as students move towards the abstract models of the world that can take them to a deeper level of understanding.

The purpose of this exploration, then, is to examine the effectiveness of using concrete physical models to help students develop abstract reasoning in an introductory physics course. Development of Free Body Diagrams was selected as the particular topic for the examination.

The remainder of this section is intended to provide physics information for readers without significant physics background but who wish to draw conclusions about this project independently from those made in the final section of this paper. In particular, information about the specific reasoning process addressed, when combined with the details of the project itself, is intended to provide insight for instructors in other fields with their own abstract reasoning challenges. It can easily be skipped with no loss of flow to the general discussion.

An Aside on Physics

The first time that students in an introductory physics course encounter a deep level of abstraction is development of Free Body Diagrams. A Free Body Diagram is a stylized representation of all of the significant forces that act on the object of interest for the given question. There is a direct tie between the Free Body Diagram and the mathematical solution to a dynamics problem, and, in fact, the physics is done in the construction of the diagram. The rest of the solution is, quite simply, algebra.

Figure 1 shows a Free Body Diagram of a sled, with a child on top, which is slowing down as it moves across level ground. Careful examination of the diagram shows that students must go through several processes of abstraction in the development of the diagram.

In the first case, students need to separate the system of interest from the surroundings, a process that is used throughout classical physics and is one of the defining elements of the process of "doing physics." Whether the sled alone is treated as the system, as is shown in the figure, or whether the sled and child together can be taken as a single system depends on the particular questions being asked, so that even this simple example begins to suggest that this is not always a straightforward process and requires both awareness and practice on the part of students.

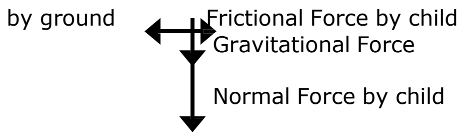

Figure 1. Free Body Diagram of a sled

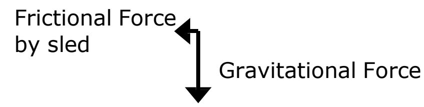

Figure 2. Free Body Diagram of a child

Construction of the Free Body Diagram also involves making sound judgments about what forces to include on the system. For example, Figure 1 includes a frictional force which the reader knows must be present because the sled is slowing down. It does not include air resistance or buoyant force of the air on the sled. Both of these, then, have been assumed to be significantly smaller in magnitude than the other forces on the sled. Ignoring insignificant effects, too, is a process common throughout physics and yet it is one that causes great frustration among many students new to the field.

A third element of the process of developing the diagram can be especially confusing to students. Forces, by their very nature, are *interactions* between two things. The Earth and the sled *inter*act gravitationally, for example, although the strength of that interaction is commonly referred to as the weight "of the sled." Language such as this, and the Free Body Diagram itself, artificially remove the interaction nature of forces from the problem. On one hand, such isolation is very useful. In order to analyze the motion of the sled, a student needs to know how interactions affect the sled but does not need to consider how those interactions affect other objects. On the other hand, conceptual questions about Newton's 3rd Law are some of the most frequently misunderstood questions in introductory physics.

Any instruction designed to help students develop Free Body Diagrams, and deepen their understanding of Newtonian Physics through that process, needs to be conscious of all three of these elements involved with making and understanding the drawings.

Method and Results

Initial Exploration

The idea for this exploration into using physical models to get at abstract ideas initially came about through discussions with an adult student with ADHD. He was very articulate about his understanding of material, which allowed insight into the particular sticking points that caused him trouble. As for other students, the step into the abstract was one where he wanted greater connection and more ways to work with the ideas. He also articulated the frustration of many students with the idea of ignoring interactions that they know are present.

As mentioned in the introduction, development of Free Body Diagrams was chosen as the topic to address through this study. It is the first time in the course that students encounter significant use of abstract diagrams, and, much like the importance of learning to read for academic success across disciplines, approaches first encountered in development of those diagrams are used again and again throughout classical physics.

A student researcher who had previously taken introductory physics was brought into the project at the planning stage. In addition to providing insight into physics from a student

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perspective, she was a strong advocate to ensure that no students were disadvantaged due to different types of instruction used in the course.

The initial (2004-05) stage of the project was purely exploratory in nature. The small number of students in the three sample groups did not allow for meaningful statistical analysis, but trends on exams and qualitative data from interviews provided a great deal of insight into student learning and informed the follow-up exploration in 2005-06.

Method

A single physics course at a small mid-Western state university was used as the study group for this exploration. 54 students (32 women and 22 men) were enrolled in the first semester of Fundamentals of Physics, an introductory algebra-based physics sequence. The vast majority of students in the course were biology majors. There was also very little racial/ethnic diversity in the course, with all but four students being of predominantly European American descent.

All students received fairly traditional instruction about how to construct Free Body Diagrams in lecture, although Newton's 3rd Law was taught before Newton's 1st and 2nd Laws and was used to establish the nature of forces as interactions. Free Body Diagrams and Newton's 2nd Law were introduced as showing the effect of all such interactions on a given object. Students were encouraged to initially name forces with descriptions (e.g. "push on the book by the table") rather than formal names (e.g. "normal force.") Lecture presentation was supplemented by in-class student work on relevant materials in *Tutorials in Introductory Physics* (McDermott et al., 2002) and the assignment of homework problems in the associated homework volume.

In addition to the common instruction, IRB approval was given to provide three different types of supplemental instruction to the students in the three laboratory sections of the course. Two of the three laboratory sections were taught by the lecture professor, who also taught both discussion sections for the course. The lecture professor provided the supplemental instruction for all three of the laboratory sections. This instruction was given at the start of the third laboratory meeting of the course, and included the same two examples ("Draw a free body diagram for a child going downhill on a sled. Draw a free body diagram for the sled." and "Draw a free body diagram for a parachutist before opening the parachute, and another diagram for after the chute was open.") in each section. In all cases, the solution to the sled question was presented on the board after the students worked on it. The parachute problem was addressed to the large group through student questions only, and was used in part to bring up questions about when forces like air resistance should be included and when they can be ignored.

18 students (8 women and 10 men) in one laboratory section formed the control group. They were given an additional 30 minutes of instruction in the same mode as was presented in lecture. All students appeared to participate fully in drawing the diagrams. Identification of 3rd Law interactions was presented as switching the words "on" and "by" in the names of the forces.

An intermediate group, based on using paper and pencil to work with the same ideas as for the fully experimental group, consisted of 10 students (7 women and 3 men.) This laboratory session met at 8:00 a.m. and the students did not appear to be fully engaged in the process, an observation which should be kept in mind during discussion of the results. In this case, students were taught to develop "system schemas" (Turner, 2003). In drawing system schema, students first represent the object of interest with a circle. As students consider other objects with which it interacts, they represent those objects also with a circle

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(all circles are named) and draw a line between the two to indicate an interaction. Free Body Diagrams are constructed by noting all of the interactions that connect to the object of interest, and 3rd Law interactions are represented by a single line on the original drawing.

The largest laboratory group (24 students, 16 women and 8 men) was given 35 minutes of supplemental instruction using play dough and tooth picks rather than pencil and paper to construct the initial schema from which the Free Body Diagrams were made (an additional 5 minutes was spent on logistics such as passing out the materials and establishing color coding for toothpicks to represent pushes and pulls). In this section, toothpicks were used to identify and represent 3rd Law interactions. Although not every student in the class used the physical materials to construct the schema, all appeared to be engaged in the process. It should also be noted that although enthusiasm of the instructor has sometimes been seen as a contributing factor to stronger student performance with a new method, that was distinctly not the case in this situation. While toothpicks and play dough provided an easy to use, inexpensive set of materials, they looked distinctly "un-college like" as the instruction date drew closer, contributing not enthusiasm but rather unease to the instructor.

Two students in the course were unable to attend at the beginning of a regularly scheduled laboratory section due to other class conflicts, and therefore started lab after the supplemental instruction was given. All other students in the course took part in one of the three sessions. In addition, willing students completed a Multiple Intelligences Inventory and/or took part in interactions with the student researcher including a post-midterm interview and e-mail response to focus questions.

Results

Both quantitative and qualitative methods were used to examine this project. The first method was to compare performance on the relevant portion of Midterm 1. This was particularly important to the student researcher as part of her advocacy that no student be disadvantaged as a result of the type of instruction that s/he received. The portion of the exam used was a three part problem involving a tractor pulling a hay wagon. Students were asked to produce Free Body Diagrams and to use those diagrams to mathematically find the size of the force between the tractor and the wagon. There was no difference in performance between the three lab groups on this problem. For all three groups, the average performance on this problem divided by total exam grade was 21%. A Z-test on the raw scores (16.1, 17.1, 16.4) also showed no significant difference in overall performance between groups. However, as seen in Table 1, the nature of the errors made was remarkably different between the groups. Students in the control and intermediate groups incorrectly identified 3rd Law pairs (a common problem) much more frequently than students who used the physical model approach, but those using physical models had a higher rate of a less-frequently seen error, double counting forces. In other words, some drew both "force on the wagon by the tractor" and "force on the tractor by the wagon" on the same Free Body Diagram. No statistical test for significance was performed on this data due to the low numbers throughout.

Section	**fraction (%) of students who incorrectly identified 3rd Law pairs**	**fraction (%) of students who double-counted forces**	**fraction (%) of students who did an excellent job on the Free Body Diagram portion**
Experimental (Manipulatives)	1/24 (4)	4/24 (17)	13/24 (54)

Intermediate (System Schema)	3/10 (30)	0/10 (0)	4/10 (40)
Control (Traditional)	5/18 (28)	1/18 (6)	8/18 (44)
Lab time conflict (None)	1/2 (50)	0/2 (0)	1/2 (50)

Table 1. Student Errors and Performance on Midterm 1 Free Body Diagram Problem

A second quantitative look at student performance in this project was done through use of the revised Force Concept Inventory (Halloun, et al., 1995) which was given as a pre-test at the start of the semester and as a post-test near the end of the semester. The Force Concept Inventory (FCI) is a 30 question, multiple choice test which asks conceptual questions about situations that can be understood by Newton's Laws or basic kinematics. Normalized gain, <g>, was used as a reliable way of comparing pre-/post-test scores (Hake, 2002). Normalized gain for each student was calculated by dividing the actual gain in test scores (post-test score – pre-test score) by the possible gain for that student (30 – pre-test score.) As can be seen in Table 2, students who worked with physical models saw a mean gain 1.5 times that of students in the control group and 1.4 times that of students in the intermediate group, although ANOVA analysis did not show this difference to be significant ($F_{2,43}=1.72$). Pre-test scores for the three groups were similar, ranging from 10.6 to 11.6. Note that because code names were used for the Force Concepts Inventory, one of the two students who did not receive supplemental instruction may be included with students in the System Schema sample group. 22 students from the experimental group, 10 students from the intermediate group plus no supplemental instruction, and 14 students from the control group took both the pre- and post-test.

Section	**Pre-test score**	**Post-test score**	**<g>**
Experimental (Manipulatives)	10.9	16.7	.344
Intermediate (System Schema)	11.6	15.2	.245
Control (Traditional)	10.6	14.9	.225

Table 2. Student Performance on the Force Concept Inventory

The third type of quantitative data that was examined was exploration into performance on the Force Concept Inventory and learning strengths as indicated by the Multiple Intelligences Inventory. No correlation or relationship of any type was found between learning styles and the effectiveness of the three types of instruction.

Two types of qualitative data were also gathered on student performance and experience in the course. 14 students (nine from the experimental group, two from the intermediate group, and three from the control group) participated in an e-mail focus group discussion with the student researcher. The purpose of the focus group was to ensure that students felt they were being treated fairly as the experiment was conducted and that they had an outlet for anonymous communication to the instructor should that be necessary. Questions therefore focused on the usefulness of laboratory and its relationship to lecture, the difficulty level of instruction, suggestions for changing the teaching of the course, and concerns that should be passed along to the instructor.

Overall, all groups found lab to be helpful, to fit well with lecture, and to be of an appropriate level, although students from the experimental group provided more detail in their response, indicating, for example, how lab helped them to visualize concepts from lecture. Three of the nine students specifically cited the Free Body Diagram activity. In terms of teaching style, again responses were overall positive and did not show variation from group to group. Suggestions were made to include more hands-on activities and to do more examples. Students also expressed appreciation for the study as an example of the instructor's interest in helping them to learn.

Qualitative data regarding student performance was collected through one-on-one interviews with the student researcher following the first midterm exam. 28 students (19 from the experimental group, three from the intermediate group and six from the control group) voluntarily took part in the interviews. Students were given a small incentive to participate: although they were required to attend and do the lab activity for that week, they were excused from the written component of lab if they participated in an interview. Interviews lasted less than eight minutes, and were intended to provide insight into the problem solving process that students went through in the three part problem discussed above. This was also a chance to correct misunderstandings about Free Body Diagrams and 3rd Law pairs. Students were asked to explain each force on their version of the Free Body Diagram and indicate why that force was included. They were also asked about the forces that they identified as 3rd Law pairs and the criteria used to determine such pairs.

Of all of the data collected, results of these interviews provided the strongest motivation for continuing the project with an entire class experiencing the physical model instruction. In the summary words of the student researcher, students in the experimental group "seemed to think about things as a whole concept" whereas the control group "seemed to just 'touch on the basics' instead of applying the basics…seemed to look for <u>clues</u> as to how to answer the question." Additional comments relating to the experimental group included an observation that the unified repetition of concepts helped with understanding and retention, and that completeness "seems to be a big deal" for the students. Many of the students in this group built their Free Body Diagrams in a circular fashion, leading to some thoughts on the origin of the double counting error. An additional observation regarding students in the control group was that at least some of them did not have criteria and did not know what to look for. Interviews with the intermediate group showed that the students found breaking down the concepts to be beneficial but did not shed light on the difficulty in identifying 3rd Law pairs.

Second Stage Exploration

Although the number of students in the first study was small, the narrative data indicating that students taught via physical models had a big picture perspective, compared to a more list-checking perspective of the traditionally taught students, led to the second stage of this exploration. Students in the Fundamentals of Physics sequence in 2005-06 were all taught Newton's Laws using the manipulatives approach as a teaching tool.

Method

Again, the first semester of Fundamentals of Physics at the same Midwestern university was used as the study group for this stage of the exploration. 60 students (42 women and 18 men) were enrolled in the course, taught by the same instructor as for the initial exploration. As for that exploration, most students in the course were biology majors. 12 students (8 women and 4 men) were identified as belonging to a racial or ethnic minority.

During this offering of the course, all students were taught to generate Free Body Diagrams using manipulatives during the lecture section of the course. As before, Newton's 3rd Law was presented before the 2nd Law and treated as a statement about the nature of forces (forces are interactions.) Instruction took place as described for the experimental laboratory group above, with several changes and additions made to the approach. The most minor change was to replace toothpicks with plastic sticks and strings to represent forces rather than using color coded toothpicks. In part this change was made due to the time and attention students spent sorting the toothpicks, and in part because the string provides a more visual distinction of attraction vs. repulsion. A more substantial change was made to address the double-counting error that four of the students in the experimental laboratory section showed with forces. Students were provided with a frame, a window cut in a section of manila folder, which they used once their physical models were constructed. The frame was placed to show the object of interest and therefore to highlight how the interactions act on that particular object without showing the other objects.

Finally, two additions were made to the approach in order to extend the use of desk top activities throughout the course. First, consistent color coding was used between notes *and activities* throughout the course, with blue (ink or play dough) representing the system of interest and red representing the surroundings which impact that system. Boxes containing a variety of materials (small slinkies, lenses, rubber and steel balls, tape, etc.) were also provided in class each day. In some cases, the materials in the boxes were used for directed activities such as the construction of Free Body Diagrams; at other times, they were available for students to help visualize the material being discussed. No other changes to homework or instruction were made.

Results

Two criteria were examined in order to explore the effectiveness of instruction based on manipulatives. The first, comparison of performance on a common problem on the final exam, tested the effectiveness of the instruction on the targeted problem (construction of Free Body Diagrams) for which it was designed. The second, students' self-reported confidence in topics during the *second* semester of the course, explored the question of whether or not the emphasis on system/surroundings for forces would generalize into other topics which require a similar distinction but which were not directly addressed through desk top activities.

Performance by students in the 2005-06 section of the course was compared to that of previous students on a common question on the final exam. Results are shown in Table 3. The exam question was essentially the same as the tractor question on the 2004-05 midterm, except in this case a horse was said to pull a sleigh. Students from 2001-02, 2002-03, and 2003-04 were taught by the same instructor at the same institution before the start of either project. Students in the course for 2004-05 participated in the initial stage of the exploration, so that a sample of them received each of the three types of instruction although all had follow-up instruction in lecture and, for some students, a meeting with the student researcher following the first midterm exam.

Section	**fraction (%) of students who incorrectly identified 3rd Law pairs or did not identify such pairs at all**	**fraction (%) of students who did an excellent job on the Free Body Diagram portion**
2001-04 sections (no manipulatives instruction)	58/180 (32)	97/180 (54)

2004-05 section (pilot study)	8/54 (15)	41/54 (76)
2005-06 section (all students received manipulatives instruction)	11/60 (18)	45/60 (75)

Table 3. Student Errors and Performance on Final Exam Free Body Diagram Problem

Unlike the initial exploration, the number of students who double-counted forces was not tallied. Although no such double counting was noticed by the instructor prior to the initial project, several of the exams (eight from 2001-2004 and two from 2004-05) showed what could, on the second look, be evidence of such double counting. For example, several students showed both "m" and "pull by the Earth" as forces acting on the horse. Without interviewing the students or having other ways to explore their understanding, it is not clear if these numbers truly represent double counting or, if so, if they include *all* students who made such an error, although in a less overt way than was seen in the 2004-05 study. No students taught in 2005-06 (using the frame to box out their schema) showed evidence of double-counting forces.

As can be seen in Table 3, the percentage of students in each of the two years of this study who incorrectly identified (or did not identify) 3rd Law pairs was about half the percentage of students who made similar errors in courses where manipulatives were not used. Similarly, about 1.4 times as many students in 2004 and 2005 sections did an excellent job on that problem compared to earlier years. χ^2 analysis showed the difference in performance regarding identification of 3rd Law pairs to be significant (χ^2 (2,294) = 8.91, p=.05). Further exploration showed that the difference in performance between the control group and the pilot study was significant (χ^2 (1,234) = 5.39, p=.05) but that the performance difference between the control group and the 2005-06 section was not. There was also no significant difference found between the 2004-05 and 2005-06 sections.

The difference in performance relating to "excellent job on the Free Body Diagram" was also found to be significant (χ^2 (2,294) = 13.8, p=.01). Additional exploration found that both the differences between the control group and the pilot study, and between the control group and the 2005-06 section were significant (χ^2 (1,234) = 7.45, p=.01 and χ^2 (1,240) = 7.45, p=.01 respectively). Again, there was no significant difference between the 2004-05 and 2005-06 sections.

The second criterion used to explore student performance was not directly tied into the manipulatives-based activity. Rather, it explored the idea that students might use reasoning built in one arena for better understanding in a related area without additional, specifically-targeted, manipulatives-based instruction. In this case, the system/surroundings color-coding system was used consistently throughout the 2005-06 Fundamentals of Physics sequence including sections on Electric Force and Field, but no activity was developed to help students develop abstract reasoning regarding the Electric Field.

The Student Assessment of Learning Gains instrument (Seymour, et al., 2000) was given at the end of the Fundamentals of Physics sequence. In 2004-05, "Electric Field" was added as a topic under the question, "As a result of your work in the class, how well do you think you now understand each of the following?" Answers were given on a 5 pt. scale (ranging from 1="not at all" to 3="somewhat" to 5="a great deal".) The mean response for the 2004-05 class section (which did not include a specific use of color-coding for system/surroundings) was 3.65. The mean for the 2005-06 section was 3.86, which was not found to be a significant difference.

Discussion

Although a variety of quantitative and qualitative approaches to understanding the impact of manipulative-based activities on an abstract-reasoning process were used, the most exciting result is the interview summary from the initial stage of the study. Having a *student* interviewer identify a pattern in which students taught via the experimental method approached problems in a more holistic way, rather than looking for clues or surface features, suggests that this approach does, indeed, make an impact on higher order thinking skills.

Quantitative assessment results are mixed; although all of the trends support a positive difference for the manipulatives-based activity, not all of these differences are significant. The most targeted measure of the impact of using the experimental approach is performance on the Free Body Diagram portions of the midterm and final exams. Although the small sample size did not allow for meaningful statistics on the midterm question, analysis of performance on the final exam shows that students in both experimental classes were significantly more likely to do an "excellent job" on the relevant exam problem than students in the control group. The difference in performance on identifying Third Law pairs was also significant for the 2004-05 experimental group but not for the 2005-06 group.

Taken together, these two targeted assessments suggest that the activity did, indeed, have an impact on the specific topic for which it was designed, and that higher order thought processes associated with that topic were addressed.

One caution should be made, however, in interpreting the results. Although the same instructor taught all five sections of the Fundamentals of Physics course used in this analysis, a text book change was made between the 2002-03 and 2003-04 academic year. One instructional change accompanied the change in text book, and that was to put more emphasis on forces as interactions before moving to Newton's Second Law. When students in the 2003-04 section were isolated from the rest of the control group, their performance mirrored both the control and the experimental group. They were similar to the control group in performance on the problem overall, suggesting the manipulatives activity was responsible for the change in that performance, but more similar to the experimental group on identifying Third Law pairs, opening the possibility that the text and instructional emphasis contributed to the improved performance on pair identification. This is not, however, supported by the interviews and difference in performance between the laboratory sections in 2003-40, all of which used the same text book and basic instructional approach but showed different rates of common errors including Third Law pair identification.

The assessments described above addressed the experimental question in a very direct way. Additional assessments used in this study explored the results more indirectly, and in particular were used to consider the impact that helping students to develop abstractions in one area might have on other, related areas. In this case, both assessments suggest that the results do not carry over, but that additional activities should be used across the course as new ideas are encountered and old built upon.

Use of the Force Concepts Inventory is one of the two indirect measures used. The FCI does not direct students to draw, or to use, Free Body Diagrams, nor does it exclusively test force-related concepts. In order to do well on this test, students need to recognize and apply basic physics to force and descriptive motion questions without obvious cues. Trends in scores on the FCI initially look very promising, with students who learned Free Body Diagrams through manipulative-based instruction outscoring their peers in both other groups. Differences, however, did not prove to be significant. This was also the case when student understanding of Electric Field was probed through use of the Student Assessment of Learning Gains instrument. Developing the idea of system/surroundings with manipulatives for Free Body Diagrams did not show evidence for significant improvement in understanding Electric Fields (also taught classically on the system/surroundings dichotomy) when no directed activities were used in that instruction.

Taken together, then, results of this study suggest that involving students in manipulatives-based activities can, indeed, help them to make transitions from concrete situations to abstractions of those situations. However, the activities appear to be effective only in the cases for which they are developed and do not, when applied in a limited way, develop abstract reasoning across other scenarios. This is the key idea that should be carried forward into courses in other disciplines. To be effective, physical modeling activities should be targeted to a particular abstract reasoning process or task, and should be designed around elements of that process. While future work is needed to explore the extent to which students generalize abstract reasoning to additional tasks in a course which makes heavy and consistent use of physical modeling, it is clear from this project that the jump is not made when such activities are used only occasionally throughout the course. The mechanism through which manipulatives make an effect was not explored in this project, aside from the experimenters' observations that use of such activities required students to slow down and attend more attention to the instruction.

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