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Do students use and understand free-body diagrams?

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Physics education literature recommends using multiple representations to help students understand concepts and solve problems. However, there is little research concerning why students use the representations and whether those who use them are more successful. This study addresses these questions using free-body diagrams (diagrammatic representations used in problems involving forces) as a type of representation. We conducted a two-year quantitative and qualitative study of students' use of free-body diagrams while solving physics problems. We found that when students are in a course that consistently emphasizes the use of free-body diagrams, the majority of them do use diagrams on their own to help solve exam problems even when they receive no credit for drawing the diagrams. We also found that students who draw diagrams correctly are significantly more successful in obtaining the right answer for the problem. Lastly, we interviewed students to uncover their reasons for using free-body diagrams. We found that high achieving students used the diagrams to help solve the problems and as a tool to evaluate their work while low achieving students only used representations as aids in the problem-solving process.

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I. INTRODUCTION AND PURPOSE OF THE RESEARCH

The conceptual knowledge in physics courses is often presented in an abstract symbolic form. The symbols have precise meanings and are combined with rules that must be used correctly. In contrast, the human mind relates best to picture-like representations that emphasize qualitative features but not detailed precise information.[1] There have now been a great many studies on physics learning indicating that students taught with an emphasis primarily on using mathematics to develop and apply concepts fail tests with seemingly simple conceptual questions that measure understanding. In these courses they learn to use formula-centered problem-solving methods with little understanding.[2]

If we want students to understand and learn to use the symbolic representations that are part of the practice of science (for example, the mathematical descriptions of processes), we have to link these abstract ways of describing the world to more concrete descriptions. A main question in this paper is to decide if a learning system with considerable emphasis on describing processes in concrete and in abstract ways and in building links between these different representations enhances student learning and problem-solving ability.

Students in courses that incorporate multiple representations have been very successful on such tests as the force concept inventory (FCI),[2] mechanics baseline test (MBT),[3] and conceptual survey of electrostatics and magnetism (CSEM) (Refs. 4–6), and in hands-on tasks.[7] But there is no literature concerning the effects of the quality of the multiple representations students construct to help with their quantitative problem solving and what they actually do while solving those problems. In this paper we provide a detailed study of student use of one of the representations, specifically a free-body diagram (FBD). This study investigates three questions:

(a) If students are in a course where they consistently use free-body diagrams to construct and test concepts in mechanics and in electricity and magnetism and to solve problems during the class, do they draw free-body diagrams on their own when solving multiple-choice problems on tests?

(b) Are students who use free-body diagrams to solve problems on tests more successful than those who do not?

(c) How do students use free-body diagrams when solving problems?

The answers to these questions will provide insights concerning the importance of multiple representations (specifically free-body diagrams) in student learning, thinking, and problem solving.

II. CONCEPTUAL FRAMEWORK

A. Problem solving: Expert versus novice

There are multiple differences in the approaches of experts and novices to problem solving.[8] Novices choose a strategy to solve a problem based on the superficial surface features while experts choose strategies based on concepts that are relevant to the problem.[8] Experts also utilize a larger number of heuristics or experimentally derived cognitive "rules of thumb.[9]" When experts use heuristics, they "chunk" the information together while novices look at the problem in pieces.[10] Novices also differ from experts in their search techniques during problem solving.[11] Novices typically first write down the known and unknown variables. Next, they use a backward inference technique—a search for equations involving variables they think they can use. Experts use a forward inference technique. A summary of the main differences between experts and novices[12] in problem solving is listed in Table I and can be found in Ref. 12.

In addition to these differences between experts and novices when they solve problems, researchers have documented

TABLE I. Differences in problem solving between experts and novices (Ref. 12).

Expert	Novice
Conceptual knowledge affects problem solving.	Problem solving largely independent of concepts.
Often performs qualitative analysis, especially when stuck.	Usually manipulates equations.
Uses forward looking concept-based strategies.	Uses backward looking means-end techniques.
Has a variety of methods for getting unstuck.	Cannot usually get unstuck without outside help.
Is able to think about problem solving while problem solving.	Problem solving uses all available mental resources.
Is able to check answer using an alternative method.	Often has only one way of solving a problem.

some differences between experts and novices when they construct representations to help them solve problems.[13–19] For example, in genetics, experts and novices differ in terms of the level of sophistication of their constructed diagrams and how they reason with their diagrams. As Ref. 16 states; "the experts displayed a variety of diagram-related reasoning behaviors such as knowledge-dependent representational variability, fine-tuning of the diagrams to the immediate reasoning task, and systematic use of fine-tuned diagrams as *tools to think with* while reasoning.[18]" Novices showed either very little or no evidence of these abilities. Similar differences were found in mathematics.[17]

Although both experts and novices in mathematics made visual representations while solving problems, novices typically did not use their visual representations to help solve the problems. Experts not only constructed visual representations more frequently but used them to explore the problem space, develop a better understanding of the situation, and to help solve the problem.[17]

Another issue is that novices may not always use the most effective representation when they attempt to solve a problem.[20,21] Usually novices proceed from an abstract verbal problem statement to an even more abstract mathematical representation[22] while an expert in the same situation would have an intermediate representation such as a picture, a graph, a force diagram, etc. Thus, it is important to create a representation-rich learning environment which helps students learn how to use different representations. Part of this environment includes helping students see how to use representations when solving sample problems and then transferring those representations to isomorphic target problems, which students can solve successfully.[23] Another integral part of the representation-rich environment is to have students solve real-world type problems via different representations while collaborating with others. Giving students a representation with a problem is not enough to help them become successful in learning and becoming confident with the content.[24] This environment can either focus on the role of representations explicitly or implicitly.[25]

B. Do multiple representations help students master physics?

In the early 1990s Van Heuvelen developed a curriculum that was based on the use of representations in his Overview, Case Study Physics (OCS).[26,27] This learning system was based on research by Larkin *et al.*,[1] Heller and Reif,[28] and others. In the OCS curriculum the instructor uses representations such as pictures, words, diagrams, and graphs to help students understand a concept and then students use these representations to solve quantitative problems based on this concept. Students' learning gains on a diagnostic test from the OCS course were 15% higher than those in a traditional class, and the OCS students were also able to retain information longer.[26]

Gautreau and Novemsky[29] reported on an adaptation of the OCS course that emphasized multiple representations and active student participation in the learning. They found that these OCS students scored significantly higher on problem-solving hour exams and on a final exam than traditionally taught students in three other sections of the same course. The exams were written by the professors in the three traditionally taught sections and taken at the same time by students from all four sections.

More recently, De Leone and Gire[30] investigated whether the use of multiple representations in courses affected student problem solving. They studied how many representations students used when solving open-ended problems on quizzes and tests. The course under study was taught via interactive engagement strategies with frequent use of different representations. De Leone and Gire found that the majority of the students used many representations such as pictures, free-body diagrams, graphs, etc. while solving the open ended problems. Also, they found that all of the students who correctly solved the majority of the problems were high multiple representations users. In all but one of the coded problems, students who used representations had a higher success rate in solving the problem. Their research suggests that if students learn physics in an environment that emphasizes the use of multiple representations, students will use them to help solve open-ended problems. However, De Leone and Gire did not assess the quality of the representations students constructed.

Students often recognize that constructing a representation is not a task in itself, but rather that a representation might help them solve the problem.[31] Van Heuvelen and Zou[31] found that students learn better if they understand the reason behind different pedagogical strategies such as using bar charts to solve problems involving energy. Student understanding and problem solving is enhanced if students

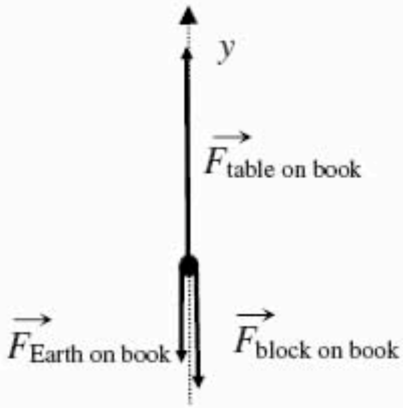

FIG. 1. An Example FBD.

learn to move back and forth in any direction between different representations[29,31] However, according to Kohl *et al.*,[25] students use representations whether they are taught explicitly or implicitly. Regardless, as we stated previously, if we want our students to become expert problem solvers, we must help them learn to construct different representations and to use them for problem solving.

C. Multiple representation example (free-body diagrams)

Much of the research described in Secs. II A and II B dealt with how experts and novices solve problems and use representations to learn. Since our study focuses on one representation in particular, the free-body diagram, we focus the rest of this section specifically on free-body diagrams (FBDs). An FBD is a diagrammatic representation in which one focuses only on an object of interest and on the forces exerted on it by other objects. Figure 1 is an example of an FBD for a book on a table with a block on top of it.

Instructors can teach FBDs in many different ways[26,28,32–38] but they all have the same goal, to help students solve problems involving forces. The method the instructor used in this study was developed by Etkina and Van Heuvelen[32] but is based upon the work of Heller and Reif.[28] We will explain this method in depth later in Sec. III.

As there are many different ways of drawing FBDs, it is important to highlight some of the differences.[34–39] Some researchers recommend special labeling techniques[35] while other researchers[38,39] have special placement of the vectors in the diagram with the forces drawn in a specific way. Some suggest that students should include the angles in the diagram.[35] Another approach involves students drawing a system schema[28,40,41] before they construct an FBD. A system schema is a pictorial representation showing the object of interest and how it interacts (via direct contact or at a distance) with other objects.

Regardless of how the free-body diagram is constructed, it helps students identify all of the forces exerted on an object of interest by other objects and then allows them to correctly apply Newton's second law in component form to determine the magnitude of the object's acceleration, or if the acceleration is known to determine the magnitude of an unknown force. This step is how FBDs play an integral part in the problem-solving process—as a transition from a concrete physical situation to an abstract mathematical equation(s).

The various ways a person can construct a free-body diagram has been well documented. However, none of the above mentioned studies discuss the relationship between the quality of the diagrams students construct and their success when they use the diagrams. One study analyzed the quality of free-body diagrams and how many students use them to solve the problems but did not relate the quality of the diagrams to student success on the problems.[42] This study investigates whether students who learn physics in an environment that explicitly focuses on multiple representations, and specifically on free-body diagrams, use free-body diagrams to help them solve problems, and whether the quality of the diagrams that students draw is related to their problem-solving success.

III. METHOD

A. Context

This study was conducted in two consecutive years in a two-semester large-enrollment (about 500 students in each of the two years) algebra-based physics course for science majors with the same instructor. The instructor of the representation-rich course followed the Investigative Science Learning Environment (ISLE) format[6,43]—a guided inquiry learning system that engages students in the active construction of knowledge mirroring the processes used by physicists to acquire knowledge. Since one of the processes that physicists use to solve problems and communicate information is representing knowledge in multiple ways,[22,26] the ISLE curriculum emphasizes the use of multiple representations. This emphasis is reflected in the course materials. *The Physics Active Learning Guide* (*ALG*) (Ref. 32) included, among other things, special innovative multiple representation tasks as separate problems. These tasks ask the students to represent the same phenomenon in different ways or to construct a new representation of a phenomenon using some other representation without having the students calculate a numerical answer. An example of a typical multiple representation task is provided in Appendix A.

During the large-room meetings, the instructor discussed with the students how to represent a process in a particular way and how to use one type of representation to help construct another. The instructor helped his students learn how to use pictorial and physical representations (motion diagrams, free-body diagrams, energy, and momentum bar charts) to reason about physical processes and to solve problems. The instructor used the following strategy to help students learn how to draw FBDs.[44] The steps listed in Fig. 2 (Ref. 45) are for a box being pulled across the floor.

(1) Sketch the situation described in the problem.

(2) Circle an object (objects) of interest in the sketch—we call this the system.

(3) Model the system as a particle (if possible). Place at the side of the sketch a "particle" dot to represent the system.

(4) Look for objects outside the system (external objects) that interact with the system.

tations for concept construction and problem solving, students construct free-body diagrams on their own while solving problems.[25] Our study does not focus on differences in instructional environments, but rather researches the role of free-body diagrams as tools helping students solve problems involving forces.

We found that although students received no credit for their work on the multiple-choice exam problems, an average of 58% drew free-body diagrams on their exams when in an environment that fostered the understanding and use of different representations in problem solving. In 8 of 12 problems more students did draw free-body diagrams than did not. This is much higher than what is found for the two problems from the control group (11% and 23%) and what was reported in the literature for traditionally taught courses (10–20 %).[22,49] The high percentage in our reformed course is similar to the numbers reported for another reformed course at another institution.[25]

We also found that the students in the course under study used free-body diagrams outside of pure mechanics. In year 1, just as many students used free-body diagrams in electrostatics as they did in mechanics. In year 2, although there were more diagrams drawn in mechanics than those drawn in electrostatics, there were still a large number of diagrams drawn in electrostatics.

We found that all students who drew a correct free-body diagram were much more likely to solve the problem correctly (Table IV). The other trend was that those students who drew an incorrect free-body diagram were more likely to solve the problem incorrectly than students who showed no evidence of using an FBD. Both of the above results were found to be statistically significant (Table V). It is important to note that "no evidence of an FBD" does not mean that the student did not use one. Students could have constructed one in their head, as was stated by a student during the qualitative study, or possibly on scrap paper that was not turned in to the proctors, as was stated by another student during the second interview.

The qualitative study expanded the quantitative study by adding the knowledge of how students use mathematical representations (MRs) to help them solve problems. We found that all six students, independent of their classroom instruction, spontaneously drew a picture when they started to solve a problem. However, only those that were taught explicitly to draw free-body diagrams while solving mechanics problems did draw them and used them to construct a mathematical representation. Out of those, only the high achieving students used the free-body diagrams at the end of the problem-solving process for evaluation and to check the consistency of their work, solution, and their representations.

There is another interesting fact about the six students in the qualitative study. As we previously stated, the students received the following grades in their second semester: Jose—A; Mary—B+; Anna—B; Eileen—C; Krutick—B; Sahana—C+. Jose maintained a grade of an A in both semesters. Mary, who used fewer representations, had her grade go from an A in the first semester to a B+ in the second. Anna, who was a low achieving student yet used a lot of representations went from a C+ to a B (no longer low achieving). Eileen, who was low achieving and used few representations only brought her D up to a C. Krutick used more representations than Sahana in the course and also received a higher grade, a B as compared to a C+. This limited amount of data we collected *suggests* that students who use representations will improve their grade.

Finally, it is important that we also discuss the limitations of our study. All of the quantitative data came from exam work only and the control group only had two of the 12 problems. We decided to continue this study for two years with two different groups of students to ensure the consistency of our findings and to help address the limitations. The quantitative study only tells us if the students marked the right answer not whether they actually solved the problem correctly and how they used the free-body diagram to get that answer. This is why we added the qualitative research aspect. However, qualitative research has its own limitations. We had the students solve just one problem. As the students in the interview study solved one problem, we could only check for consistency between that problem and their exam work.

V. IMPLICATIONS FOR INSTRUCTION

The students in our study used FBDs to help solve problems when no credit was given for using the diagrams. Many of the students used them not only for understanding the problem statement, but to help construct the mathematical description of the problem and to evaluate their results. We feel that these results can be attributed to several aspects of the leaning system.

(1) Students saw the value of the diagrams when in an environment where they learned how to use FBDs for concept development, for problem solving, and for conducting experimental investigations.

(2) Students acquired a habit of using the diagrams and did so automatically when in an environment when representations were used consistently in the large-room meetings, recitations, and instructional laboratories.

Learning to evaluate the consistency of different representations with respect to each other and to use them to evaluate their solutions is a very valuable ability that this learning system helped some students acquire. In short, we feel that emphasizing representation-based approaches to concept construction, problem solving, and instructional laboratory investigations results in student use of the representations for effective problem solving.

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