FREE-BODY DIAGRAMS: NECESSARY OR SUFFICIENT?

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Abstract. The Rutgers PAER group is working to help students develop various scientific abilities. One of the abilities is to create, understand and learn to use for qualitative reasoning and problem solving different representations of physical processes such as pictorial representations, motion diagrams, free-body diagrams, and energy bar charts. Physics education literature indicates that using multiple representations is beneficial for student understanding of physics ideas and for problem solving. We developed a special approach to construct and utilize free-body diagrams for representing physical phenomena and for problem solving. We will examine whether students draw free-body diagrams in solving problems when they know they will not receive credit for it; the consistency of their use in different conceptual areas; and if students who use free-body diagrams while solving problems in different areas of physics are more successful then those who do not.
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INTRODUCTION

An external representation is something that stands for, symbolizes or represents objects and/or processes. Examples in physics include words, diagrams, equations, graphs, and sketches. The positive role of multiple representations in learning has been suggested by many [1-5]. H. Simon said: “Finding facilitating representations for almost any class of problem(s) should be seen as a major intellectual achievement, one that is often greatly underestimated as a significant part of both problem solving efforts in science and efforts in instructional design.” [6]. A free-body diagram (FBD) is one representation used by physicists while representing processes involving forces. Physics instructors teach students how to draw the diagrams and encourage student to use them in problem solving [7-9]. However, there is little evidence that those who draw free-body diagrams are more successful in problem solving than those who do not. We also do not know if students actually use FBDs beyond mechanics.

This manuscript investigates three questions: a) do students draw free-body diagrams while solving problems if they know there is no credit associated with this work; b) are students consistent in using free-body diagrams in different conceptual areas, and c) are students who use FBDs to solve traditional problems more successful then those who do not?

COURSE DESCRIPTION

This study was conducted in a two-semester large-enrollment algebra-based physics course for science majors. There were two 55-min lectures, one 55-min recitation and one 3-hr laboratory per week. The course followed the Investigative Science Learning Environment (ISLE) format [10]. Helping students learn to represent physical phenomena in multiple ways is one of ISLE’s essential features.

In the course under study students learned to use motion diagrams, free-body diagrams, energy and momentum bar charts and so forth to reason about physical processes. As these representations are specific to physics, we call them physical representations [3]. Students also used pictorial and mathematical representations. The course had a specially designed packet that included, among other things, multiple representation tasks as separate problems [11]. In each lecture the instructor (AVH) discussed with the students how to approach several representation tasks and how to move from graphical representations to the mathematical. Then students worked individually and in small groups on similar activities. Feedback to the students was provided orally or via an electronic Personal Response System (PRS). Special multiple representations tasks occupied 40% of the recitation time. Drawing a physical representation was a part of the problem-solving strategy that AVH followed closely in lectures and students were encouraged to use in recitation and homework problems. Model solutions for the homework included a special step – drawing a physical representation of the problem situation.

FREE-BODY DIAGRAMS

While helping students learn to construct free-body diagrams we used the following strategy. Circle the object of interest in a sketch of the situation. Look for objects that touch the object or that interact with it at a distance. Represent each interaction with a force arrow. The number of the force arrows should equal the number of objects with which the object of interest interacts. Each force is labeled with two subscripts: for example: $\vec{F}_{\text{E on b}}$ would identify the force exerted by the Earth on the ball [6]. The relative length of the force arrow represents the relative magnitude of the force. The diagram must agree with other representations, for example the acceleration arrow in a motion diagram.

In lectures AVH consistently used FBDs to analyze phenomena and to construct the mathematical expression of Newton's second law in component form. In recitations students practiced drawing diagrams as separate exercises and then used them to write Newton's second law to solve problems. Model solutions for the homework problems emphasized free-body diagrams and their relationship to the component form of Newton's second law. In the second semester, free-body diagrams were used by AVH in electrostatics and magnetism to solve problems involving forces.

INSTRUMENTS/PARTICIPANTS

There were two midterms and one final each semester. The exams were predominantly multiple-choice with some hand-graded sections. We tried to devise specific multiple-choice problems that included several objects and would be difficult to solve without drawing free-body diagrams. The problem statements did not specifically ask for a diagram. The multiple-choice questions were graded with Scantron sheets. Students did not receive any partial credit for work or diagrams. We chose 5 exam problems from 4 exams for this study [see appendix].

We looked at FBDs that students drew on the exam sheets near the problem statement. If there was no diagram, we scored the response as 0. If a student drew the diagram but made mistakes in it (wrong forces, arrow length or mislabeled) we scored it as 1. If a student drew a diagram correctly with enough information to solve the problem, we scored it as 2. We related the scores to the students' answers.

We have complete data for 125 students. These 125 students came from an original sample of 200 students chosen randomly from 560 students in the first semester (10 students from each of the 20 recitation sections). Some did not take the second semester and some missed one of the exams reducing our final number to 125. The grade breakdown for the students in the study was almost identical to the breakdown for the class. Thus we believe that the sample was representative of the student population.

FINDINGS

Question (a) Do students draw free-body diagrams while solving problems if they know there is no credit associated with this work? To answer this question we counted all students who drew diagrams independently of whether the diagrams were correct or not [Table 1]. We found that 15% of students in the sample drew a diagram for <u>each</u> of the five problems chosen for the study (3 mechanics and 2 electrostatics); 72% of the students in the sample drew FBDs for at least one problem in mechanics and at least one in electrostatics; 12% drew free-body diagrams only for mechanics problems; 10% drew free-body diagrams only for electrostatics, and 5% never drew a free-body diagram [Table 2].

TABLE 1. Comparison of Students who Drew a FBD and those that did not (N=125).

Question	# who Drew a FBD	# who did not Draw a FBD
Mech. Exam 1 Qstn 1	94	31
Mech. Exam 1 Qstn. 2	63	62
Mech. Final	49	76
Electrostatics Exam 1	73	52
Electrostatics Final	91	34

TABLE 2. Consistency of Students Usage of FBD in Mechanics and Electrostatics (N=125).

Case	Percentage
Used in all 5 Problems	15
Used in at least one Mechanics & Electrostatics	72
Used only in Mechanics	12
Used only in Electrostatics	10
Never Used	5

Research question (b) Are students consistent in using free-body diagrams correctly? We found that 24% of the students drew a FBD correctly each time they attempted one, 26% drew correct diagrams for the majority of their attempts, 18% drew an equal number of correct and incorrect FBDs, 10% drew the majority of their FBDs incorrectly, and 2% got every diagram wrong. We put 14% of the students separately as they drew only one FBD for the five questions, thus we could not check for consistency. Another indication of consistency was that 5% of the students never drew a free-body diagram [Table 3].

TABLE 3. Consistency of Students Usage of FBD Associated with Correctness of Use (N=125).

Case	Percentage
All FBD Correctly	24
Majority of FBD Correct	26
Number Correct = Incorrect	18
Majority of FBD Incorrect	10
All Incorrect	2
One FBD Drawn	14
None Drawn	5

Research question (c) Are students who draw free-body diagrams to solve traditional problems more successful in solving the problems then those who do not? To answer this, for each exam problem we broke the students into 3 groups [Table 4]: students who drew a perfect free-body diagram; students who drew a diagram but made mistakes in it, and students who did not draw an FBD. Then we calculated the percent of the students in each group who chose the correct answer (first three columns). The fourth column represents the "success rate" for each problem. We measured the "success rate" of a problem as the percentage of students in the sample who chose the right answer for that problem. Table 4 provides additional data about the number of students who chose a correct answer divided by the number of students in each group.

DISCUSSION

There is little information in the literature [12] about student use of diagrams on tests in traditional courses (especially when diagrams are not required). Thus our study provides a contribution to the research of the role of free-body diagrams in successful problem solving. We realize the limitations of study: all data came from exam work only and there was no control group. We summarize our findings below.

Many students draw free-body diagrams: Students received no credit for their work on multiple-choice exam problems. Still, many of them drew FBDs. Table 1 shows that in most cases, there were more students drawing free-body diagrams than students who did not draw free-body diagrams (the only exception was the Mechanics final).

Students use free-body diagrams in more then mechanics situations. We found that students did use free-body diagrams while solving both mechanics and electrostatics problems. Roughly 3/4ths of the students we tracked used these diagrams while solving mechanic and electrostatic problems.

Students are consistent. Students are somewhat consistent in using free-body diagrams. Half of the students coded were consistently correct in using free-body diagrams.

Students who drew a correct free-body diagram were more likely to correctly solve the problem: We found that students who draw a free-body diagram correctly while solving a problem are much more likely to solve the problem correctly [Table 4]. We also found that drawing an incorrect FBD led to more incorrect solutions than having no diagram at all. In other words a wrong FBD is worse than no FBD at all. The distracters (possible answers due to incorrect reasoning process) for the electrostatics exam 1 problem should probably be revised so that students with incorrect diagrams are less successful.

TABLE 4. Comparison of Free-Body Diagrams Drawn to Answers Given (N = 125).

Exam Question [Rubric Score]	FBD Correct 2	FBD Incorrect 1	No FBD 0	Success Rate
Mechanics Exam 1 Question 1	61/79 = 77%	5/15 = 33%	18/31 = 58%	84/125 = 67%
Mechanics Exam 1 Question 2	45/51 = 88%	2/12 = 17%	19/62 = 31%	66/125 = 53%
Mechanics Final	12/22 = 55%	4/27 = 15%	24/76 = 32%	40/125 = 32%
Electrostatics Exam 1	49/55 = 89%	13/18 = 72%	33/52 = 63%	95/125 = 76%
Electrostatics Final	37/46 = 80%	14/43 = 33%	12/36 = 33%	63/125 = 50%

What are possible explanations of our findings? One can speculate why students did or did not draw free-body diagrams while solving a particular problem. We are currently conducting interviews to find whether it was just a habit developed in the course or students found diagrams helpful for solving difficult problems, and did not use them when they perceived problems as easy. A possible explanation for why drawing an incorrect diagram is related to a worse performance is that the students who had no FBDs could possibly draw them in their minds and did this correctly, or used some other approach to a problem, while those who did draw an incorrect diagram obviously misunderstood the physics. Obviously more studies are needed to rule out these explanations.

APPENDIX

Mechanics Exam 1, Question 1

A 100 kg fireman starts at rest and slides down a vertical pole with a constant downward acceleration of 4.0 m/s^2. The magnitude of the friction force that the pole exerts on the fireman is closest to:

Mechanics Exam 1, Question 2

Assume that the 100 kg fireman was traveling at a speed 6.0 m/s when he reached the floor. He managed to stop the center of his body in 0.40 m by bending his ankles and knees. What was the magnitude of the average force of the floor on his feet while stopping him?

Mechanics Final

Block A of mass 6.0 kg rests on a smooth table and is connected by a string that passes over an ideal pulley to block B of 4.0 kg. Block B is released from rest. Which answer below is closest to the time interval that block A, initially at rest, needs to travel 0.80 m?

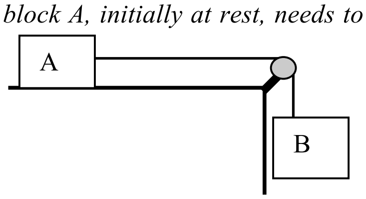

FIGURE 1. Picture with Mechanics Final exam question.

Electrostatics Exam 1

The three charged metal balls each have a charge of magnitude Q but of different signs, as shown. The positive direction is towards the right. Which expression below is the net electric force exerted on the right charged ball?

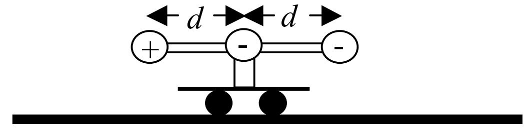

FIGURE 2. Picture with Electrostatics Exam 1 question.

Electrostatics Final

A small metal ball with +2.0 μC of charge hangs at the end of a vertical string. A second identical ball with -2.0 μC of charge hangs at the end of a second vertical string. The tops of the strings are brought near each other and the strings reach an equilibrium orientation (no longer vertical) when the balls are 3.0 cm apart. If the gravitational force of the Earth on each ball is 30 N, what is the tension in one of the strings?

REFERENCES

1. J.I. Heller and F. Reif, "Prescribing effective human problem solving processes: Problem description in physics," Cognit. Instruct. 1, 177-216 (1984).
2. J. Larkin, “Understanding, problem representations, and skill in physics,” Thinking and Learning Skills, 2, 141-159 (1985).
3. A. Van Huevelen, “Learning to think like a physicist: A review of research-based instructional strategies,” Am. J. Phys., 59, 891-897 (1991).
4. R. Dufresne, W. Gerace, and W. Leonard, “Solving Physics Problems with Multiple Representations,” Phys. Teach. 35, 270-275 (1997)
5. D. Hestenes (1997), Modeling Methodology for Physics Teachers. In E. Redish & J. Rigden (Eds.) The changing role of the physics department in modern universities, AIP Part II. p. 935-957.
6. H.A. Simon, Models of discovery and other topics in the methods of science, Dordrecht:Reidel (1977).
7. D.P. Maloney, “Forces as Interactions,” Phys. Teach. 28, 386-390 (1990).
8. A. Puri, “The art of free-body diagrams,” Phys. Educ. 31, 155-157 (1996).
9. B. Lane, “Why can’t Physicists draw FBD’s?” Phys. Teach. 31, 216-217 (1993).
10. E. Etkina and A. Van Heuvelen, “Investigative Science Learning Environment: Using the processes of science and cognitive strategies to learn physics” Proceedings of the 2001 Physics Education Research Conference. Rochester, NY, 17-21 (2001).
11. A. Van Heuvelen and E. Etkina, Physics 203/204 Activity Guide, University Press, E. Brunswick, NJ (2003).
12. Harper, K. A., Investigating the Development of Problem Solving Skills during a Freshman Physics Sequence, Unpublished PhD dissertation, The Ohio State University, (2001).