Addressing Student Difficulties with Buoyancy

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Abstract. This study is part of an ongoing effort to develop a diagnostic test assessing student understanding of fluids. In particular, this paper addresses a question involving density and buoyancy, which was used in the study of reference [1]. The "five blocks" question, which asks students to predict the final location of blocks released from rest when submerged and explain their reasoning, has been administered to hundreds of students in three different introductory courses at Grove City College for the past four years. We used the common student responses to craft a multiple-select version of the five blocks problem in 2008. This paper will present the effects that changing workshop activities have had on student performance on the five block question.

Keywords: Buoyancy, Fluids, Archimedes' Principle, Education Research.
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INTRODUCTION

Fluids are covered in all three versions of introductory physics at Grove City College (GCC), and we have been developing a standard assessment to gauge student learning of this material. Initially, the assessment was an ad-hoc effort, including long-response questions from references [1-2] along with a few quickly-composed multiple choice questions. We are currently in the process of producing a set of more robust multiple-choice questions based in part on responses to the original version of the assessment and drawing upon references [1-3]. This paper will discuss the results of a question pertaining to buoyancy and show how student performance on that question has been affected by changes in workshop activities.

DESCRIPTION OF THE SAMPLES

Introductory physics is taught each year to three distinct populations at GCC:

- Physics 101 ("Calc") is a calculus-based introductory course covering mechanics and fluids. Typically three 50-minute lectures and one 2-hour workshop meeting (using one or two of McDermott's *Tutorials* [4]) are devoted to fluids topics. Instructors for the Calc course did not change over the duration of this study.
- Science 201 ("GenEd") is a one-semester concept-based course. The course content is very broad, including mechanics, fluids, circuits, magnetism, ray optics, and some modern physics. Historically, two and a half 75-minute lectures and one ~75-minute workshop (on Archimedes' principle) have been devoted to fluids. In the spring of 2009, the fluids activity was expanded to use the full 2-hour period by adding a series of questions involving forces and free-body diagrams, motivated in part by reference [4]. The lecture professor for the GenEd course did not change over the duration of this study. Workshop instruction was shared each semester by several professors, but they worked together to present a fairly consistent approach.
- Physics 121 ("Trig") is a trigonometry-based introductory course covering mechanics and fluids. Historically three 50-minute lectures (and no workshops) have been devoted to fluids topics. In 2008, a 2-hour workshop activity on fluids was added and the lecture professor changed.

THE FIVE BLOCKS QUESTION

A two-page fluids assessment was given to each class post-instruction in Fall 2005 (F05) and has been given pre- and post-instruction ever since. Up through Fall 2007, the fluids diagnostic used a free-response version of the five-block question taken directly from reference [1]. The full text of this question is found in Figure 1 on the next page. Multiple correct answers to are possible; two are Diagrams A and D in Figure 2. As was found by the original study, the most common response (Diagram B in Figure 2) is incorrect and involves a "linear" arrangement of the blocks, with depth proportional to density. (Between 34% and 78%

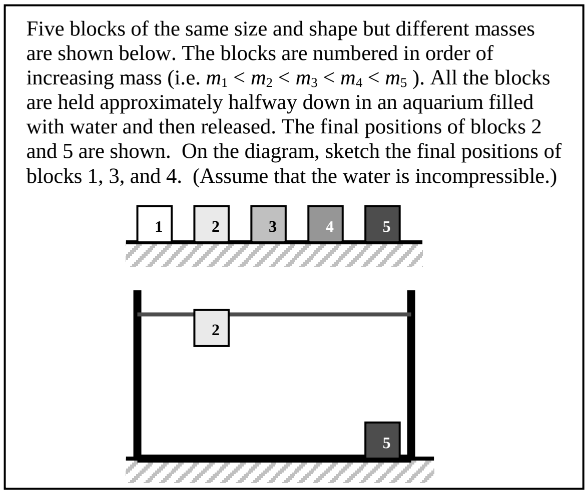


FIGURE 1. The original five-block question.

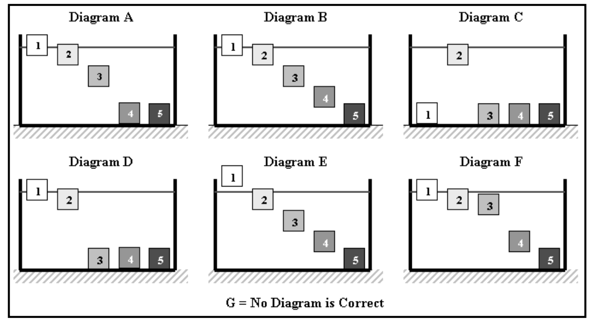


FIGURE 1. Options for the multiple-select version of the question. The text is the same as in Figure 1, except that students are asked, "Which of the following diagrams display(s) possible final positions of the five blocks? Circle all which apply." (Block 3 in Diagram F is clearly under the water line in the students' version, even though this reduced image does not show the distinction clearly.)

of GCC students, depending upon the course/semester, drew a "linear" model post-instruction.)

In Fall 2008, we switched to a multiple-select version of the question (possible answers shown in Figure 2), including the two correct answers (Diagrams A and D), three "linear" answers (Diagrams B, E, and F), and another answer (Diagram C) that occurred regularly. We included Diagram E, which shows block 1 floating in air, after wondering whether these responses were intentional or due to poor drawing. A significant number (between 8% and 38%, depending on sample) of students choose this option in the multiple-select version. Understanding why students choose Diagram E is a topic of ongoing study.

For the multiple-select version, we included only A, only D, and only A and D as "correct" answers. Choosing one or more of the correct options together with one or more of the linear options (B, E, and/or F) was designated as "mixed." The data for the multiple-select version are found in Figure 3, on the right of the dashed vertical line.

Introducing the multiple-select version of the five-block question resulted in significantly lower results for the Calc and GenEd courses, neither of which had any substantial instructional changes. (Significance was determined by using a two-by-two mixed model ANOVA with repeated measures on one factor, using $\alpha = 0.05$. Changes between semesters were analyzed using both a "semester" comparison that identifies whether the average scores (pre and post combined) differ and an "interaction" comparison that essentially compares the pre-post gain of different semesters.) For the Calc course, we saw a significant difference between the question versions in both the "semester" comparison ($p < 0.001$), and the "interaction" comparison ($p = 0.027$). For the GenEd course, the overall average scores were lower on the multiple-select version ($p < 0.001$ for the semester comparison) but the pre-post gain was equally flat for both question versions ($p = 0.213$ for the interaction comparison). The Trig pre-test results were lower on the multiple-select question version as well, but a new activity (discussed below) led to a rise in the post-test results.

Lower scores (pre-tests and GenEd post-test) appear to be affected by the question version more strongly than higher scores, making learning gains more pronounced on the new version. We believe that the new version of the question is more discriminatory primarily since it includes the possibility of choosing both correct and incorrect answers. (Between 34% and 71% of students fall in the "mixed" category on the multiple-select version, depending upon the sample).

COURSE MATERIALS AND RESULTS

Physics 101 (Calc)

The workshop portion of the Calc course uses many tutorials from reference [4]. Two tutorials, "Pressure in a Liquid" and "Buoyancy," cover fluids topics; which tutorial(s) was (were) used and what other activity was completed during the 2-hour session varied from year to year. The Calc course used the Buoyancy tutorial in each year of this study except 2006, as indicated by the stars in Figure 3. This course does not include any hands-on study of fluids. To our knowledge, the fluids coverage in lecture did not change significantly over the course of this study.

The correlation between performance on the five blocks question and completion of the Buoyancy tutorial is not surprising. While the tutorial does not explicitly include a question like the five blocks or "teach to the test," the tutorial was developed by the

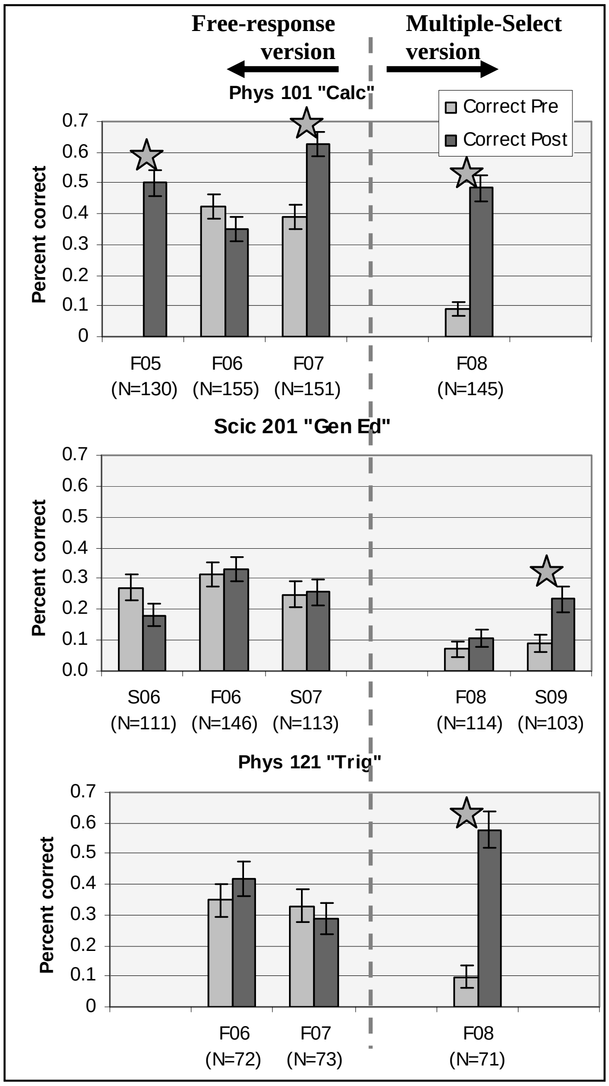


FIGURE 3. Data for the five-block question. The multiple-select version was introduced in Fall 2008 (F08), as indicated by the vertical dashed line. Error bars are standard deviations of the mean using a binomial (1 if correct, 0 if incorrect) approach. Semesters marked with a star used a workshop activity consisting of or motivated in part by McDermott's Tutorials [4]. The assessment was not given pre-instruction in F05.

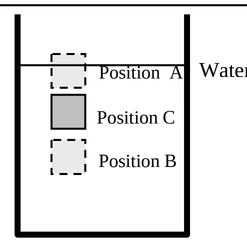
Washington PER group, presumably in response to their findings in [1]. This tutorial asks students to draw free-body diagrams and predict future motion for blocks of various densities (greater than that of water and less than that of water) submerged and released. Students develop the concept of the buoyant force as the net force due to pressure. The strong correlation between tutorial completion and performance on the five blocks question, along with the dismal performance on the question in the other courses, motivated changes to activities in the other courses.

Science 201 (GenEd)

The GenEd workshop included an experiment on Archimedes' principle throughout the duration of this study. Students determined the mass of displaced water and compared to the mass of floating and sunken objects. They also considered what happens to the level of water in a container when items are "thrown overboard" out of a floating boat. The activity is not "cookbook" but includes many reflection questions and applications.

As the GenEd data in Figure 3 show, this experiment does not seem to have had a significant impact on performance on the five blocks question and thus we question its efficacy in helping our GenEd students understand buoyancy. Our ANOVA analysis for the three free-response GenEd semesters shows no significant difference (p = 0.32) between pre- and post-test results, and no significant difference between the three semesters, when the test and activity were unchanged; p = 0.12 for both semester comparison and interaction comparison. Poor performance on this single question does not, of course, indicate a complete lack of understanding of all aspects of buoyancy, but one would hope that an increased understanding of buoyancy would lead to an improvement in student performance on this question. Our ad-hoc diagnostic does include other questions, and analysis of those results is ongoing.

A certain time after the block was released from position B, it has risen to position C.



21. How does the buoyant force on the block when it is at position C compare to the buoyant force on the block when it was at position B? (Hint: how does the difference in depth between the top and bottom surfaces compare?)

F_B IS GREATER AT C. F_B WAS GREATER AT B.

F_B IS THE SAME AT C AS IT WAS AT B.

22. Draw a free-body diagram for this block when it is at position C in the space to the right, using arrows to represent the two (vertical) forces acting on the block. The length of the arrow should indicate the magnitude (strength) of the force. Each arrow should be labeled to indicate the force it represents.

FIGURE 4. Sample questions added to the GenEd activity.

In Spring 2009 (S09) we modified the GenEd activity by adding a section at the beginning involving free-body diagrams for objects of various densities released from underwater, motivated by the success of our Calc students who used the "Buoyancy" tutorial of [4]. Typical questions are included in Figure 4 above. The resulting activity is a little long, and the GenEd students had great difficulty with the free-body diagrams, but we did see an improvement in performance The difference between F08 and S09, both of which used the multiple-select diagnostic version, was shown by our ANOVA analysis to be significant for both semester comparison (p = 0.046) and interaction comparison (p = 0.027). The results are still not optimal, but the improvement in results suggests that our modifications to the activity are on the right track.

Physics 121 (Trig)

Before 2008, the Trig course covered fluids only in the lecture portion, not in workshop. In the fall of 2008, a workshop activity was introduced combining parts of the GenEd experimental investigation of Archimedes' principle with free-body diagram questions motivated by both fluids tutorials of reference [4]. As Figure 3 shows, the resulting improvement in the five blocks question was impressive. Our ANOVA analysis showed that the difference between the two pre-2008 semesters was not significant (p = 0.22 for interaction comparison and p = 0.26 for semester comparison) but the introduction of the activity in 2008 did lead to improved pre-post gain (p < 0.001 for interaction comparison of 2008 and pre-2008). (The semester comparison between 2008 and pre-2008 showed no significant difference in average score, $p = 0.898$, since the pre-test scores went down and the post-test scores went up in 2008.)

Unfortunately, the introduction of this activity coincided with a change of lecture professor and the move to the multiple-select version of the diagnostic question, making causality identification a bit more complicated but not impossible. As discussed above, the change in question format generated a *decrease* in performance when instruction did not change, consistent with the pre-instruction results for the Trig students. The new lecture professor was teaching the material for the first time, and FMCE [5] results for the Trig course decreased from F07 to F08. Thus we are fairly confident that the dramatic improvement in performance on the five block question seen in F08 can be attributed to the introduction of the workshop activity.

CONCLUSIONS AND FUTURE WORK

As was noted in reference [1], student difficulties with questions such as the one in our study can be due to a complex combination of ideas and preconceptions and thus can be difficult to address. Measuring the buoyant force on floating and sunken objects was not enough to help our GenEd students understand how objects behave when released below water. Combining that experiment with a series of force analysis questions motivated by [4] moderately helped the GenEd students and greatly improved the performance of the Trig students. The revised GenEd activity exposed the great difficulty these students have with forces and free-body diagrams, which could explain why the improvement was not more significant. (The Calc and Trig courses each devote multiple workshop activities on forces and free-body diagrams; the GenEd course has spent little lecture time and no workshop time on free-body diagrams.) For the fall of 2009 we plan to replace one of the course's three kinematics workshops with a tutorial focusing on free-body diagrams and see if this additional exposure to free-body diagrams helps students consider buoyancy in terms of forces later in the course.

Analysis of the other questions on our ad-hoc diagnostic continues; that data will help us better interpret the effects of the various activities.

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