AC 2008-943: SOME IMPLICATIONS FROM PHYSICS EDUCATION RESEARCH FOR TEACHING PROBLEM SOLVING IN GENERAL PHYSICS

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Introduction

Traditionally one of the major goals of general physics courses is to help students develop problem solving skills. But while this goal is widely acknowledged by instructors for these courses, what they mean by it is seldom explicitly identified. Often instructors assume that everyone understands that the process of having students solve the "problems" found at the ends of the chapters of traditional physics books will promote student learning of both "the physics" and of problems solving skills. Physics education research over the last 25-30 years has called these assumptions into question.

With regard to learning "the physics" (developing a deep conceptual understanding of the concepts, principles and relations) the evidence is clear that traditional instruction, including having students work the typical word "problems" found in physics texts, is unproductive, perhaps even counter-productive[1-3]. In other words, students can learn to solve such tasks mechanically, but they are not solving these "problems" with understanding. However, even if we acknowledge this outcome, don't these "problems" help students learn problem-solving skills?

Answering this question requires defining what is meant by a problem and identifying what problem-solving skills we want the students to learn. In general physics courses "problem" often means the verbally-described situations for which students are to find specific numerical values of explicitly identified quantities, i.e., end-of-the-chapter numerical exercises (EOCNE's). And in most cases these tasks are written so that they contain just the information needed to be able to apply a specific relation—equation—to the given quantities to calculate the unknown quantity. But, as one research study[4] reports:

> "However, our findings, as well as those from other studies (Larkin, 1981, 1983; Larkin et.al., 1980b; Simon & Simon, 1978; Sweller, 1988), suggest that student-directed problem-solving activities not only encourage the development of formulaic approaches to problem solving, but also are inefficient for promoting desirable problem-solving strategies."

If we are really trying to help students develop robust/real world problem solving skills, is our current approach effective, or even useful? Let's consider the question a different way. Johnstone[5] has developed a categorization scheme for problem types based on data given, method to be used, and goal. The eight resulting problem types are:

Type	Data	Methods	Goals/outcomes
1	Given	Familiar	Given
2	Given	Unfamiliar	Given
3	Incomplete	Familiar	Given

4	Incomplete	Unfamiliar	Given
5	Given	Familiar	Open
6	Given	Unfamiliar	Open
7	Incomplete	Familiar	Open
8	Incomplete	Unfamiliar	Open

Looking at this scheme it is pretty clear that the vast majority of tasks that students encounter in academic situations fit into types 1 to 3, but real world problems are more commonly in types 4 to 8. So how do we help students develop the skills they need to tackle those types of problems?

What is a Problem?

What then specifically are we trying to accomplish when we work to help students develop their problem-solving skills? In order to answer this question we need to define what we mean by a problem and what particular procedures we want to get the students engaged with.

One useful definition of problem, due to Hayes[6], states:

> Whenever there is a gap between where you are now and where you want to be, and you do not know how to find a way across that gap, you have a problem. (1981)

There are two important things to notice about this definition. First it defines a problem as an interaction between an individual and a task or situation. That means that tasks in and of themselves are not problems, the problem only arises when particular individuals interact with the task. (This is why "problems" was used in the introductory section of this paper for the verbally-described situations students are assigned towork.) Second any task or situation where the individual knows how to close the gap is NOT a problem. In other words, any time an individual encounters any task/situation that really is a problem for that individual, there will be an element of novelty for the individual in the task/situation. Notice that using this definition of a problem the traditional tasks used in general physics courses are problems for the majority of students, but these tasks are NOT problems, by this definition, for physics instructors. Of course this definition would include many of the tasks/situations practicing scientists or engineers encounter in everyday endeavors as problems for them.

If we want to argue that we are teaching problem solving skills, then we ought to be talking about skills that have some general applicability, especially since most of the students in general physics courses are not physics majors. For these non-major students, many of whom are engineering majors, to apply the concepts, principles, and relations effectively they need to understand them. This in turn implies that we should be using a broad definition of a problem as our basis. The definition above fits this requirement. So what is required to solve tasks/situations that fit this definition of a problem and what skills does a solver need?

There are a number of ways to think about the problem solving process. For example, there are strategic heuristics such as the IDEAL approach[7] consisting of Identify, Define, Explore, Attack, and Learn, and there is the classic framework of Polya[8]. For the purposes of this paper, and using the definition above, we will think about the process as involving two steps: understanding (determining) the nature of the gap and searching for a way to cross the gap. Furthermore we will focus on one aspect of each of these two stages, representations for understanding the nature of the gap stage and heuristics for the searching stage.

Representations

So what are problem representations and why are they important? A problem representation is the mental model of the task that the solver constructs. For example, consider the Nine Dots task. In this task the individual is presented with the arrangement of nine dots shown in Figure 1.

Insert Figure 1 about here.

The task is to connect the nine dots with four straight lines without lifting your pencil or pen from the page and without retracing any segment of any line. This task is difficult for most people; it definitely qualifies as a problem for them. Research has shown that the nature of the difficulty is the initial representation that almost everyone forms. In the common initial representation, the solver includes the constraint that the four straight lines have to fit within the square formed by the arrangement of the nine dots. Someone attempting to solve this task with this constraint has an impossible challenge since it cannot be done, indeed to draw the four lines appropriately you must go outside the "box" formed by the nine dots.

Representations are very important in the problem-solving process because it is actually the representation that the problem solver works on. If the solver constructs an accurate representation he/she is on the way to solving the problem, but if the solver constructs an inappropriate representation he/she will not be able to make any real progress until he/she re-represent the problem accurately. One implication of this feature of problem solving is that effectively representing and re-representing problems is an important problem solving skill. And this skill includes being aware of the nature of representations and the possible need to represent a problem.

So what does the research tell us about the students use of representations when tackling the traditional tasks they encounter in general physics classes? In some research reported in 1980 Larkin, McDermott, Simon and Simon[9] found that novice physics students when presented with typical "problems" from the end of the chapter of a popular general physics text conceptualized their job as that of the finding the appropriate mathematical equation that could be used to calculate the numerical value requested. Such a representation quickly leads the students to employ "plug and chug" as the solution process. Other studies and all physics instructors are familiar with this student behavior.

The issue of representations appears in another way in physics problems. There has been recent research[10,11] on how students handle different types of physics representations such as verbal descriptions, equations, graphs, and diagrams. It is important to realize that while there is a relation between these representations and the mental model the problem solver forms, it is the latter that I am referring to when I use the term representation.

Heuristics

After a person has constructed a representation of a problem they have to complete the second part of the process—searching for the (a) solution. If the task the person is facing is indeed a problem for them then, as mentioned above, there is an element of novelty in the situation. This novelty means either that the person doesn't have the knowledge to solve the problem, and therefore must acquire it, or that they have the knowledge but don't know what or how to apply it to this situation. In either case the individual has to search for a way to bring the appropriate knowledge to bear. Humans have tools for carrying out this search and they are called heuristics.

Before talking about some heuristics we might wonder what heuristics are and what evidence there is for humans employing such tools. Heuristics can be defined as general procedures that can help the solver determine the specific solution process. Perhaps the easiest way to explain heuristics is by example. Suppose a person is working on a problem and they are stuck, but they happen to know, or strongly suspect, what the answer is. A common heuristic one is likely to use in such a situation is working backwards. This qualifies as a heuristic because one can use it on many types of problems in many domains, so it is general, however, this procedure usually does not work to directly solve the problem, but rather to give insights to the specific procedures needed. Heuristics can be contrasted with algorithms which are procedures specific to a particular type of problem and which, if applied properly, are guaranteed to produce a solution.

With regard to evidence for humans employing heuristics a study by Kotovsky and Simon[12] is one that supplies support for people behaving this way. The researchers presented subjects with the Chinese Ring puzzle, which consists of six metal rings that are interconnected on a metal loop. The rings are connected by rope or metal rods, which interweave around/through the metal loop. The goal of the puzzle is to remove the six rings from the loop. This is a complex and challenging puzzle, but the important aspect of the puzzle for the research study is that the solution process is linear in the sense that there is a specific sequence of moves that must be made to solve the puzzle.

The researchers presented each subject with the puzzle set to a particular number of steps from solution and asked them to solve it. They were video taped and asked to think aloud as they worked on the puzzle so their work could be carefully analyzed. One part of the analysis involved plotting a graph of number of steps from solution versus total number of moves made. The graphs for all subjects had the same basic structure shown in Figure 2.

Insert Figure 2 about here.

The important aspect of these graphs is the initial period where the subject is seemingly randomly moving toward and away from the solution. Notice that once this period is over, the subject moves directly to the solution. It is in this initial period that the subject is employing heuristics to learn enough about the problem domain to figure out how to solve the problem. One of the common heuristics people apply here is trial and error, but there are others. Being aware of what other heuristics there are and how to use them effectively is an important problem solving skill.

The research of Larkin et. al[9]. was mentioned above with regard to what it told us about the representations students constructed. However, that research also provided insights into heuristic usage by the students. What they found was that the students essentially employed a specific form of a general heuristic called means-ends analysis. In means-ends analysis the individual identifies the goal, where he/she is relative to the goal, identifies possible procedures that could reduce the gap, applies one of these procedures, and then evaluates whether they have solved the problem, or at least moved closer to the solution. A specific form of this heuristic is well known to math, physics, and engineering instructors—plug and chug. And if we think about the representation that most students develop for the typical physics task they face, we should not be surprised that they apply this heuristic. After all if the goal is to find a numerical value given a number of other numerical values, then the most efficient way to do it is to find the right equation.

There is another aspect to the students using the means-ends heuristic and that has to do with the cognitive resources they have to employ. Looking back at the description of the process in the last paragraph we can readily see that applying this heuristic requires a lot cognitively since the individual is monitoring a lot of information while also modifying that information and comparing the outcome to the goal. Sweller and colleagues in several studies[13,14,15] make the argument that when the students employ this heuristic they have very little in the way of cognitive resources left to devote to actually learning the concepts, principles and relations they are using. In other words they can't learn much about what most of us would call the physics while using this heuristic.

Now one of the often identified steps in the general problem solving strategies that many workers have developed is the review step, e.g., the Learn step in the IDEAL framework mentioned above. So if a person does stop after solving the problem and review what he/she has done and how it relates to the concepts, principles, and relations they are supposed to be learning, application of the heuristic may not be detrimental to learning the "physics". However, most people do not review! Kim and Pak[3] provide evidence that this does not happen for most students studying physics. Consequently, using the means-ends heuristic could easily be counterproductive to learning the "physics".

But maybe we shouldn't be too worried if the students aren't learning the physics from doing these tasks if they are developing problem-solving skills. If we take having and being able to use heuristics effectively as one of the important problem solving skills that they should be learning then the evidence is not reassuring on that count either. Singh[16] gave her subjects a task that was a problem for both the novice physics students and the experts in her study. When she examined how the two groups performed, a clear difference was found in the ability to use heuristics effectively. Neither group of subjects was able to solve the task, however, the experts did use heuristics that would have enabled them to eventually solve the problem. The novices showed very little evidence of having heuristic tools available to them.

Alternate Formats

If one of the major goals of having students take a general physics course is for them to develop problem-solving skills the evidence available at this time clearly indicates that the current diet of almost exclusively "end-of-the-chapter numerical exercises (EOCNE's)" is not productive and may actually be counterproductive. So the obvious question is what do we do? I would argue that we need to change the diet. But I want to be VERY CLEAR AT THIS POINT that I do not think the "end-of-the-chapter numerical exercises" should be completely eliminated from the diet. They do, however, need to be only a small part of the diet.

What needs to be added to the diet? I believe that the diet needs to be modified to help students realize the importance of representations, and how to modify them when necessary, and to both become aware of and learn how to use heuristics. With regard to the second aspect I think it is important to realize that students will use means-ends analysis in their problem solving efforts because they do not have sufficient domain knowledge to do anything else.

One way to address the issue of representations is to add to the diet tasks where the students will not generate the same representation as they do for the EOCNE's. An example of such tasks is a Ranking Task[17,18]. In a Ranking Task the students are presented with a set of variations, usually 4 to 6, of a basic physical situation where two or three parameters vary among the items. The students then have to rank the variations on some specified basis, which may depend on none, one, two, or all three parameters. In addition they have to explain the reasoning behind their ranking. See the example in Figure 3.

Insert Figure 3 about here.

Ranking tasks accomplish the goal of getting students to use different representations by changing the focus of the task from finding a particular numerical value to comparing situations on the basis of a specified physical quantity. In other words, they have to decide how they think the target physical quantity depends on the other physical properties in the situation. And since they are comparing variations, they are more likely to think in terms of "does more mass mean farther distance or less" rather than "what equation do I need?" Making this change forces the students to both represent the problem differently and either to employ means-ends analysis in a different way, or to use different search heuristics. In the former case an equation is no longer the obvious way to get to the solution, since a particular numerical value is not the goal, so they need to think of some means besides an equation to reach this goal. And in the latter case the student may simply think they can use the heuristic of process of elimination to rank the choices on the basis of one of the parameters given.

Ranking tasks can also be used to help students better understand equations as models—representations—of physical systems and how common sense ideas they have affect how they try to apply equations. For example, the ranking task shown in Figure 4 was given as a homework task in a general physics course enrolling engineering technology majors after Newton's second law had been introduced. Two thirds of the students (19/29) produced a ranking of E first, A and D tied for second, C fourth, B fifth and F last. This ranking sequence was obtained by taking the product of the masses of the tugboats times the accelerations of the systems. Doing this is consistent with the common sense idea that forces are things, or properties of objects, that can be transferred from one object to another. A number of students actually explicitly stated this in their explanations. Having the students solve the task using this conception can be useful because doing so helps to make it clear to the students that they have ideas that need to be changed.

Insert Figure 4 about here.

I stated above that we should expect students to use means-ends analysis no matter what. The reason for this is that means-ends analysis is a reasonable heuristic that we all use when attempting to solve a problem where we either don't know the relevant domain knowledge, or have it but don't know that we need to access it. A moment's thought given that the students will use means-ends analysis, can we find a way to make them use it in a different way than looking for an equation? Consider the following task.

> Describe a physical situation to which the following relation would appropriately apply:

$$\mathbf{(2600\ kg/m^3)(9.8\ m/s^2)(4.5 \times 10^{-3}\ m^3) - T - (8.5\ kg)(9.8\ m/s^2) = 0}$$

This task is an example of a Jeopardy problem[19]. Clearly these tasks change the goal from finding a particular numerical value to describing an appropriate physical situation. Once again this change forces the students to represent the problem differently and even if they use means-ends analysis their usual approach of finding an equation is useless since that is actually the starting point. In these tasks the students need to search for a way to interpret the given information as an alternative model of the physical situation. In other words they need to think of equations as something other than simply a calculating process. Very few students think of the equations in any other way. (A reasonable answer for this Jeopardy problem is shown in Figure 5.)

Insert Figure 5 about here.

These tasks also require students to pay attention and use certain information that they most previously ignored. Specifically in the Jeopardy problem above, in order to determine a reasonable physical situation we need to identify the physical quantities that are in the equation. To do this we have to use the units. So the units become important information that must be used to identify the physical quantities involved, and from the physical quantities, and their relationship identified by the equation, we can develop a reasonable idea of an appropriate physical situation.

At this point in time we do not have specific research data that having students work these alternate types of problems will improve their general problem-solving skills, but we do have definite results telling us that the traditional approaches are not accomplishing this goal, nor the goal of helping the students learn the physics. We also have data showing that interactive engagement approaches that incorporate the techniques mentioned, along with others, do produce improved performance on conceptual instruments like the Force Concept Inventory. A proposal to alter the "problem" diet for the students along the lines proposed here is at least reasonable based on the research results we do have. And considering the range of types of problems, whether classified according to the Johnstone scheme or any other, that these students will actually encounter in professional practice, wouldn't it be better to at least alert them to the fact that they will face many different types. Students leaving school having seen only EOCNE's, or types 1 to 3 in the Johnstone scheme, could easily be at a major disadvantage when faced with other types of problems.

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Nine Dots Problem

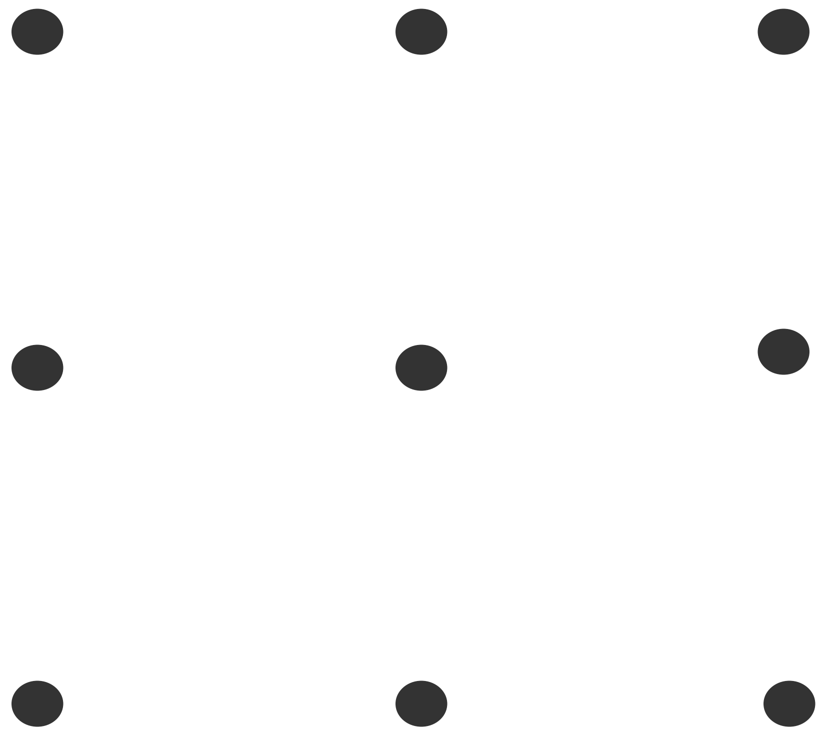


Figure 1

Chinese Ring Puzzle Study

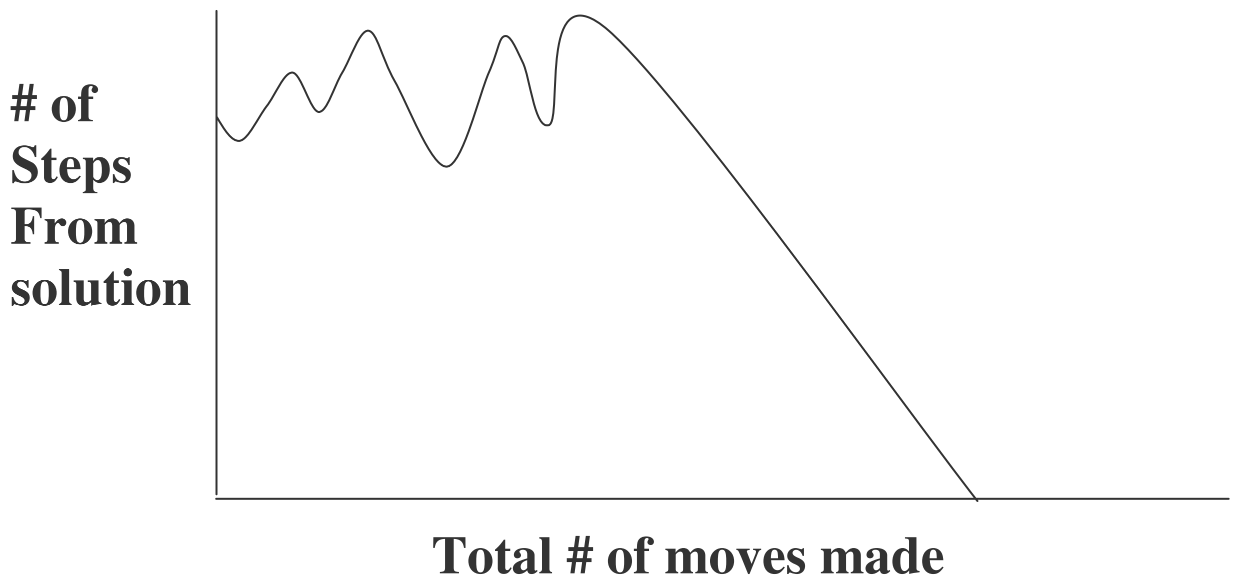
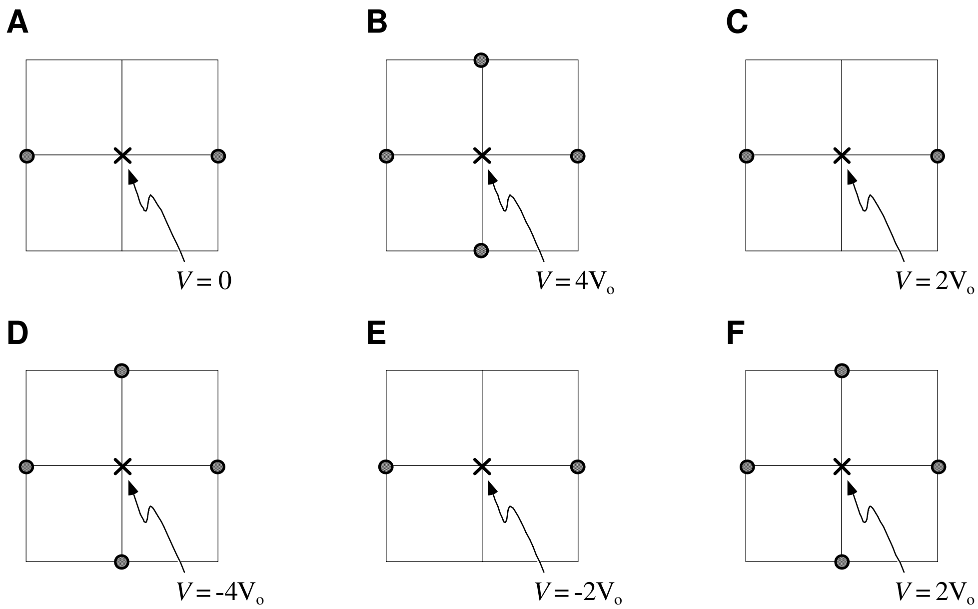


Figure 2

POTENTIAL NEAR CHARGES—ELECTRIC FIELD

In each situation below, electric charges are arranged at equal distances from a point with a specified potential. All of the charges have the same magnitude, but the signs of the charges are not given.



Rank the strength (magnitude) of the electric field at the point where the potential is given.

Greatest 1 _____ 2 _____ 3 _____ 4 _____ 5 _____ 6 _____ Least

OR, the electric field has the same non-zero strength in all these situations. _____

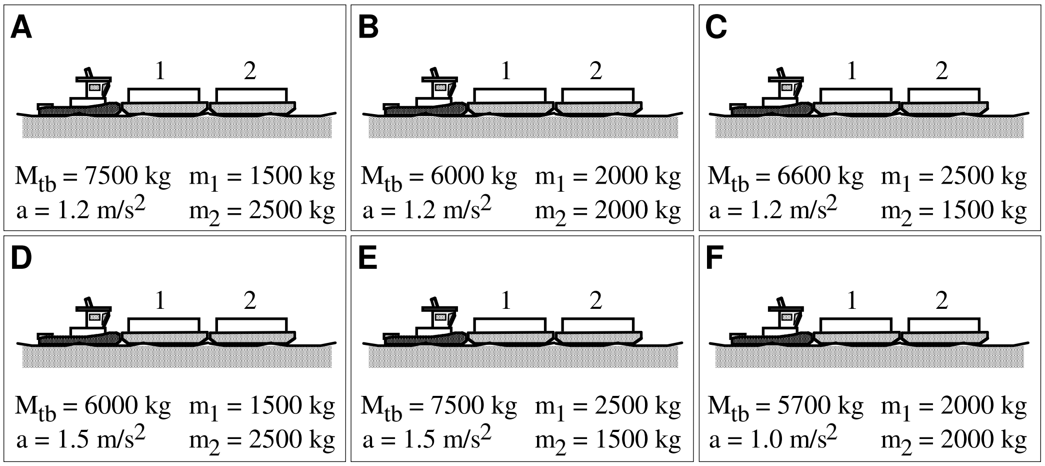
OR, the electric field is zero for these situations. _____

OR, the ranking for the electric field cannot be determined. _____

Carefully explain your reasoning.

Figure 3

In each of the six figures below a tugboat is pushing two barges. The systems of tugboats and barges are accelerating at different rates to the right. The barges have different loads so they have different masses, and the tugboats have different masses also. Values of these quantities are given in the figures.



Rank these situations from greatest to least on the basis of the force the tugboat exerts on barge one (1).

Greatest 1 _______ 2 _______ 3 _______ 4 _______ 5 _______ 6 _______ Least

OR, The forces the tugboats exert on barges one are the same for ALL SIX systems. ___

OR, The tugboats do not exert any force on barges one for ALL SIX systems. ___

OR, We cannot determine the ranking for the forces the tugboats exert on barges one of these systems. ___

Please explain carefully your reasoning.

Figure 4

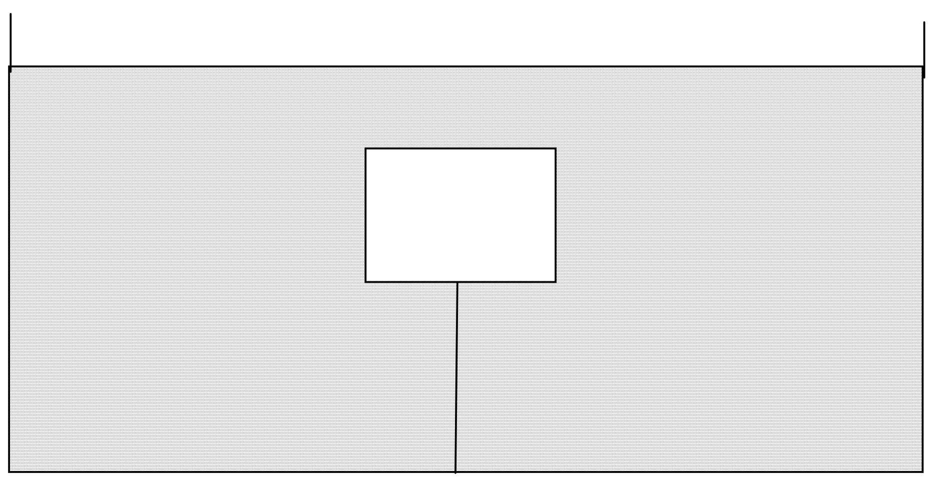


Figure 5