Student learning of physics concepts: efficacy of verbal and written forms of expression in comparison to other representational modes*

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Abstract

Physics instruction includes a variety of representational modes including diagrammatic, mathematical/symbolic, and verbal (oral and written passages employing ordinary language). Instructors attempt to assess students' understanding by observing their problem-solving performance employing this variety of representational modes. An important issue that this study investigated is the possible discrepancies in student learning abilities when using oral and written forms of expression in comparison to diagrammatic and mathematical forms. Another issue explored is the accuracy of assessment of student learning via written and oral descriptions of their reasoning, in comparison to their mathematical/symbolic problem-solving performance.

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I. Introduction

The goal of this investigation is to probe the role played by diverse representational modes in the learning of physics concepts. We explore the relationship between the *form of representation* of concepts in physics, and students' ability to learn these concepts. We are attempting to determine the specific learning difficulties that arise as students struggle to master concepts posed in different representational forms, and we plan to apply our findings to the development of improved curricular materials and instructional methods. The particular focus of this paper is to compare student thinking when using a "verbal" form of representation (written or oral) to the thinking that is manifested with other forms of representation such as mathematical, diagrammatic, and graphical.

Much previous research has shown that the use of multiple forms of representation in teaching concepts in physical science has great potential benefits, and yet poses significant challenges to students and instructors. Facility in the use of more than one representation deepens a student's understanding, but specific learning difficulties arise in the use of diverse representational modes.

By "representational mode" we mean any of the widely diverse forms in which physical concepts may be understood and communicated. For instance, problems or principles may be stated in verbal form, using words only, or purely in mathematical form, using equations and special symbols. As an example of the use of diverse representational modes, consider Coulomb's law. In Quiz #11 shown on page 16, we present four different representations of what is essentially the *identical* problem. These are posed in four distinct representational modes – verbal (#1), diagrammatic (#2), mathematical/symbolic (#3), and graphical (#4). Although to the expert these four problems are nearly identical and merely represent four different aspects of the same concept, to an introductory student they may appear very different.

What we are concerned with here are (1) common, widespread learning difficulties encountered by *many* students, and (2) the *relative degree of difficulty* of different representations in a specific context. It is often assumed by instructors that a representation that they find particularly clear and comprehensible (e.g., a graph) will also be especially clear for the average student. Research and experience shows that this is often *not* the case, but relatively little study has been devoted to this issue.

In the remainder of this paper, some preliminary results of this investigation will be presented. In Section II, I discuss some of the well-known learning difficulties that are associated with technical terms in physics that also carry meanings in "ordinary" language that diverge widely from their physics definitions. In Section III, I describe an example of a related, though somewhat distinct problem: students' alternative interpretations of words in ordinary language that have specific and precise meanings when they are employed in a technical context. In Section IV, I present results of several different probes of students' ability to interpret and respond to physics questions when posed (nearly) simultaneously in a variety of diverse representational modes.

II. Confusion due to technical terms with “everyday” meanings

It is well known that numerous technical terms in physics have everyday meanings that are very different from their “physics” definitions. The physics concepts represented by these terms are, in themselves, difficult for most students to grasp. The fact that students are burdened with alternative meanings and connotations for these words, drawn from their day-to-day experiences, significantly adds to the difficulty of learning these concepts. A few of the most prominent terms in this category are these:

***force*:** Although the ordinary meaning of force in the sense of “push” or “pull” is in itself not misleading from the technical physics standpoint, the vector nature of forces – that is, that each force is characterized by a precise magnitude and direction – is not always appreciated by introductory students. Moreover, everyday connotations of *force* such as “energy” or “power” can be extremely misleading to students (Williams, 1999), and the mistaken impression that a force is an entity in itself – rather than an *interaction* between two objects – can make it difficult for students to grasp what is, from the physicist’s standpoint, the most significant characteristic of the force concept (Touger, 1986, 1991).

***power*:** In everyday language this word is often taken to mean “energy” (or sometimes “force”), while its precise physics meaning as *energy per time* is frequently obscured. This confusion can be particularly troublesome in the context of electricity, where the word *power* is confused not only with “energy,” but often with both “current” and “voltage” (see discussion below.)

***current/voltage*:** Most introductory students make little or no distinction between the meanings of *current* and *voltage*¸ and often confuse *power* with both of these two. All three terms are broadly conceived as connoting a form of electrical “energy,” which may help explain the extremely widespread student misconception that a battery always supplies the same current regardless of the specific circuit in which it is placed. The precise physics definitions of *current* (charge flow per time), *voltage* (electric potential difference), and *power* (energy per unit time) are among the most difficult to communicate to introductory students (McDermott and Shaffer, 1992; Shaffer and McDermott, 1992).

***work*:** The everyday notion of *work* as implying “exertion” is an impediment to grasping the physics definition, in which *displacement* of an object acted upon by a force is required in order to qualify for nonzero work. The fact that the *work* done on an object in a physics sense can be either positive or negative – depending on whether the object’s kinetic energy is increased or decreased, respectively – has proven to be a particularly difficult concept to communicate to introductory students (Loverude, Kautz, and Heron, 2002). In the context of thermodynamics, difficulty in grasping the distinctions among *work*, *heat* and *internal energy* is a major obstacle to students’ understanding of the first and second laws of thermodynamics (Loverude, Kautz, and Heron, 2002; Meltzer, 2001, 2002). In part, this is due to the fact that all three quantities are measured in the same (energy) units (Meltzer, 2002).

***heat*:** In physics, heat (or “heat transfer”) is a process-dependent variable and represents a *transfer* of a certain amount of energy between systems due to their temperature difference. However, among beginning science students, heat is frequently viewed as an intensive quantity –

that is, as a mass-independent *property* of an object – and temperature is interpreted as degree of heat, that is, as a measure of its intensity. Alternatively, heat is often interpreted as a specific quantity of energy *possessed* by a body (an extensive quantity), with temperature being the measure of that quantity (Zemansky, 1970; Kesidou *et al.*, 1995; Greenbowe and Meltzer, 2002). This confusion is not restricted to the English language, for terms equivalent to *heat* in other languages such as *Wärme* [German] (Berger and Wiesner, 1997) and *chaleur* [French] (Tiberghien and Delacôte, 1978) have been associated with similar pedagogical difficulties.

III. Confusion due to ambiguous meaning of words used in a technical sense: Example of word "*constant*"

There are many instances where certain words – although they are not in a strict sense technical terms – have a specific interpretation in a technical context that can easily be misunderstood by the student. For example, in physics it is extremely common to speak of "constant" values for some variable. This means that some quantitative measure for that variable has an unchanging magnitude, characterized by a specific number in some unit system. An object moving in one direction that has a "constant" acceleration is one whose speed changes by the same amount during each second. Such an object (if its mass does not vary) must be subject to a net force whose direction and magnitude do not change with time.

Williams (1999) has argued that use of the word "constant" could improve the precision of a particular statement of Newton's first law, viz.,

> Every body continues in its state of rest or of uniform speed in a straight line unless it is compelled to change that state by forces acting on it.

Williams states:

> Two alternative word choices could improve the precision of this statement:
>
> (1) replacing the adjective "uniform" {*consistent in conduct or opinion; having always the same form, manner, or degree; not varying or variable*} by "constant" {*something invariable or unchanging: as a number that has a fixed value in a given situation or universally…*} moves from a word of everyday speech with its accompanying vagueness to a familiar and more precise word in common use in mathematics; (Williams, 1999, p. 675)

However, although the word "constant" does indeed have a precise mathematical meaning, it is not necessarily the case that this meaning is the one that will be imputed to it by the typical student. This became evident during the course of a lengthy post-instruction interview with a student in an elementary physics course. This student had just completed a hands-on, inquiry-based elementary course in which kinematics and Newtonian dynamics were the central concepts discussed throughout the course.

The student was explaining her answers to a series of questions involving a sled being pushed along a frictionless, icy surface. A person wearing spiked shoes is pushing the sled. The first question was,

> Which force would keep the sled moving toward the right and speeding up at a steady rate (constant acceleration)?

Among the answer options were:

> The force is toward the **right** and is of **constant** strength (magnitude).
>
> The force is toward the **right** and is **increasing** in strength (magnitude).
>
> The force is toward the **right** and is **decreasing** in strength (magnitude).

[Emphasis in original; first statement is correct]

I repeated the question and asked the student to explain her answer:

> DEM: Suppose she is speeding up at a steady rate with constant acceleration. In order for that to happen, do you need to apply a force? And if you need to apply a force, what kind of force: would it be a constant force, increasing force, decreasing force?
>
> *STUDENT: Yes you need to have a force. It can be a constant force, or it could be an increasing force.*
>
> DEM: . . . She is speeding up a steady rate with constant acceleration.
>
> *STUDENT: Constantly accelerating? Then the force has to be increasing . . . Wait a minute . . .The force could be constant, and she could still be accelerating.*
>
> DEM: Are you saying it could be both?
>
> *STUDENT: It* ***could*** *be both, because if the force was increasing she would still be constantly accelerating.*
>
> DEM: What do we mean by constant acceleration?
>
> *STUDENT: Constantly increasing speed; a constant change in velocity.*

It seems evident that the student is interpreting the meaning of the word "*constant*" not as "unchanging," but rather as "persistent" or "ever-present." Its precise quantitative connotation appears to be lost on her.

IV. Multiple representations of knowledge: student understanding of "verbal" representation contrasted with understanding of other forms of representation (mathematical/symbolic; graphical; pictorial/diagrammatic)

A. "Ordinary Language" vs. Graphical Representation

A major focus of our recent work has been to explore the question of whether students' ability to learn specific physics concepts may be greater when using one form of representation, rather than another. The origin of our interest in this question was the inquiry-based elementary physics course referred to above. After the introduction of microcomputer-based laboratory tools, we found that students' ability to give correct responses to questions involving Newtonian dynamics posed in graphical form seemed to have significantly increased. However, when the questions were posed in the form of "ordinary" language, no corresponding improvement was evident (Meltzer *et al.*, 1997).

Evidence for this discrepancy was provided by students' responses to questions drawn from the "Force and Motion Conceptual Evaluation" (Thornton and Sokoloff, 1998). A set of nearly identical questions related to Newton's second law are given first in ordinary language in the form of the "Force Sled" questions (see next page), and later in the form of "Force Graph" questions (following page). The only significant difference between the questions is that the first set is posed in verbal representation, while the second uses a graphical representation. Students enrolled in this physics course had literally dozens of hours of practice, both in class and on homework assignments, with very similar questions posed in both formats.

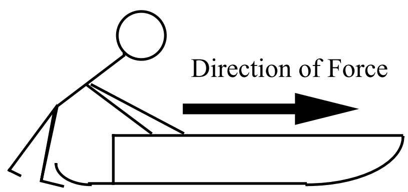
These question sets were administered post-instruction in two separate offerings of this course. A total of 18 students responded to the questions. The results are shown in the table below:

	Correct Responses, Post-instruction ($N = 18$)
Force Graph questions	56%
Force Sled questions (#1-4)	28%

In view of the great similarity of the question sets, such a large difference in correct response rates – consistent over two separate course offerings – was surprising. (A test for comparison of binomial proportions yields $p = 0.09$, marginally significant, but probably reflective of the relatively low sample size.)

A sled on ice moves in the ways described in questions 1-4 below. *Friction is so small that it can be ignored.* A person wearing spiked shoes standing on the ice can apply a force to the sled and push it along the ice. Choose the one force (**A** through **G**) which would **keep the sled moving** as described in each statement below.

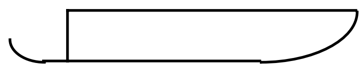
You may use a choice more than once or not at all but choose only one answer for each blank. If you think that none is correct, answer choice **J**.



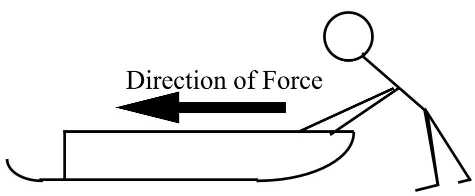
A. The force is toward the **right** and is **increasing** in strength (magnitude).

B. The force is toward the **right** and is of **constant** strength (magnitude).

C. The force is toward the **right** and is **decreasing** in strength (magnitude).



D. No applied force is needed



E. The force is toward the **left** and is **decreasing** in strength (magnitude).

F. The force is toward the **left** and is of **constant** strength (magnitude).

G. The force is toward the **left** and is **increasing** in strength (magnitude).

______1. Which force would keep the sled moving toward the right and speeding up at a steady rate (constant acceleration)?

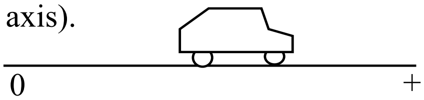
______2. Which force would keep the sled moving toward the right at a steady (constant) velocity?

______3. The sled is moving toward the right. Which force would slow it down at a steady rate (constant acceleration)?

______4. Which force would keep the sled moving toward the left and speeding up at a steady rate (constant acceleration)?

"Force Sled" Questions from the Force and Motion Conceptual Evaluation (Thornton and Sokoloff, 1998).

Questions 14-21 refer to a toy car which can move to the right or left along a horizontal line (the positive part of the distance axis).



Assume that friction is so small that it can be ignored.

A force is applied to the car. Choose the one force graph (**A** through **H**) for each statement below which could allow the described motion of the car to continue.

You may use a choice more than once or not at all. If you think that none is correct, answer choice **J**

__14. The car moves toward the right (away from the origin) with a steady (constant) velocity.

__15. The car is at rest.

__16. The car moves toward the right and is speeding up at a steady rate (constant acceleration).

__17. The car moves toward the left (toward the origin) with a steady (constant) velocity.

__18. The car moves toward the right and is slowing down at a steady rate (constant acceleration).

__19. The car moves toward the left and is speeding up at a steady rate (constant acceleration).

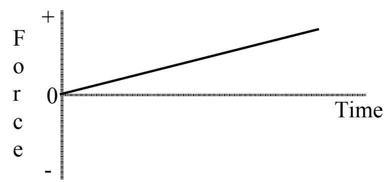
__20. The car moves toward the right, speeds up and then slows down.

__21. The car was pushed toward the right and then released. Which graph describes the force after the car is released.

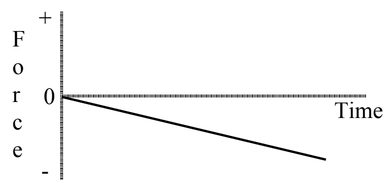
A

B

C

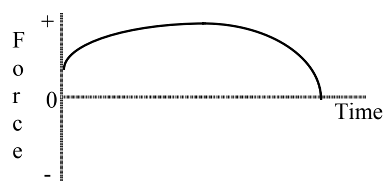


D

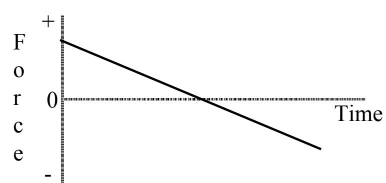


E

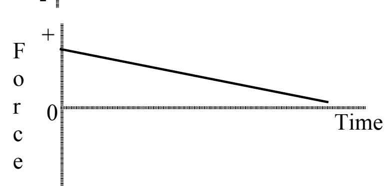
F



G



H



J None of these graphs is correct.

"Force Graph" Questions from the Force and Motion Conceptual Evaluation (Thornton and Sokoloff, 1998).

In post-instruction interviews with one of the students in this course (the same student quoted earlier in this paper), it became evident that the student did not necessarily make a connection between the methods she had learned to analyze dynamical questions by using graphical representations, and the intuitive methods she was accustomed to using in order to make decisions about what happens in everyday life. In the interview segment below, the student is asked to explain the answers she had written down when responding to the Force Sled questions shown above.

DEM: I need you to explain #3 [Force Sled Question #3]. ***["The sled is moving to the right. Which force would slow it down at a steady rate (constant acceleration)?"]***

STUDENT: [reads answer she chose] ***"The force is toward the left and is decreasing in strength."*** *. . . I was picturing the sled, and I was thinking that it would take less force once it started slowing down . . . I don't know . . .*

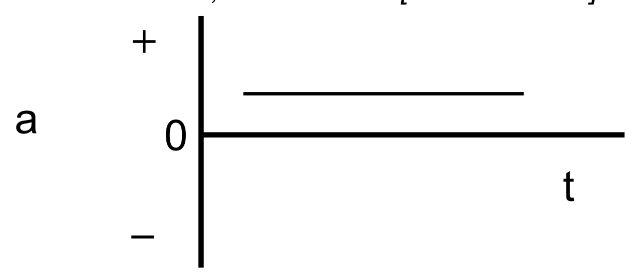
You want it to slow down at a steady rate. So since it's moving towards me and I want it to slow down, I'm actually going to have to go with it . . . and I guess I would ***increase*** *my force to slow it down, not decrease it. I don't know . . .*

DEM: Does the fact that it says "constant acceleration," does that help you to figure this out?

STUDENT: Only in so far as if the acceleration is constant, then the slope is zero . . .

DEM: The slope of what?

STUDENT: The slope of the acceleration, and so the slope of the force is going to be zero: they mirror each other. The force is going to be constant. [Draws graph to explain her reasoning.] *When I think of constant acceleration, I think of this [horizontal line].*



DEM: Now, on this one we've gone all the way around. At first you said less force was needed once it started slowing down, then you said maybe you have to increase the force. And now you're saying, "constant force."

STUDENT: Well, according to what I know, or what I think I know about graphs, I would say that the force had to remain constant because the acceleration is constant.

According to the visual image I have in my head, if a skater was coming towards me and I wanted to slow her down at a steady rate, I don't think that my force would be constant. I don't know ***why*** *I don't think that, I just think it would take less force towards the end.*

The student has apparently learned a particular algorithmic procedure for interpreting the meaning of "constant" acceleration and for relating those words to the correct response to a force question when expressed in graphical form. (That is, she says: "*When I think of constant acceleration, I think of this [horizontal line]*," and she also knows that the slope of the force and the slope of the acceleration must be the same because "*they mirror each other*.") However, it seems evident that she has not been able to make a connection between the understanding of the graphical representation of this physical situation, and her intuitive understanding of the way things actually work in the real world. Because of that lack of full understanding of the concept of Newton's second law, when a question about an object undergoing constant acceleration was posed to her in natural language form (that is, the Force Sled questions), she responded with an incorrect answer, rather than make use of the correct analysis she offered when analyzing the situation from a graphical perspective.

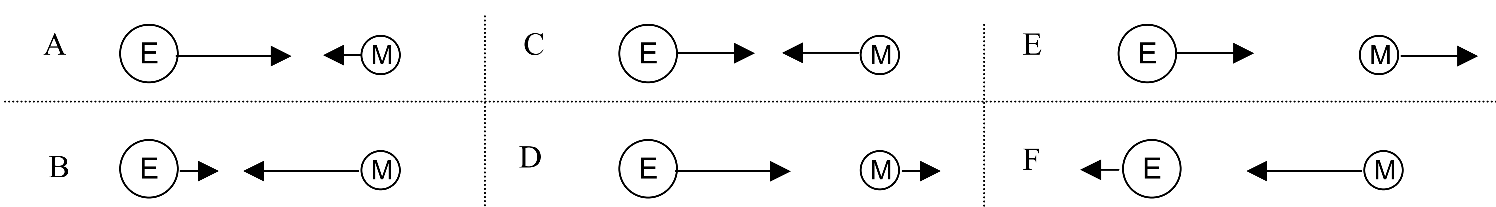
B. "Matched Sets": Similar test items posed in different representational modes

In other work, we have posed similar "matched sets" of questions to students in which other physics concepts were targeted. For example, in a question related to Newton's third law and his law of Universal Gravitation, a quiz containing the following two questions has been given over the past seven years, pre-instruction, to students taking the second semester of an algebra-based introductory physics course. (These students had all spent one full semester or more studying Newtonian mechanics, including the law of gravitation.)

#1. The mass of the sun is about 3 x 10^5 times the mass of the earth. How does the magnitude of the gravitational force exerted by the sun <u>on the earth</u> compare with the magnitude of the gravitational force exerted by the earth <u>on the sun</u>? The force exerted by the sun <u>on the earth</u> is:

A. about 9 x 10^{10} times larger
B. about 3 x 10^5 times larger
C. exactly the same
D. about 3 x 10^5 times smaller
E. about 9 x 10^{10} times smaller

#2. Which of these diagrams most closely represents the gravitational forces that the earth and moon exert ***on each other***? (Note: The mass of the earth is about 80 times larger than that of the moon.)



According to Newton's third law, the answer to both questions is that the mutual forces exerted by the interacting objects (sun and earth in Question #1, earth and moon in Question #8) are *equal* in magnitude. Therefore, the answer to both questions is "C."

These questions were both very difficult for the students, even though they all had studied the relevant concepts in their previous physics courses. In the table below, results are shown for four separate offerings of this course.

Question #1 response	**1998**	**1999**	**2001**	**2002**
A	*	*	8%	16%
B	*	*	62%	67%
C	14%	10%	23%	13%
D	*	*	6%	3%
E	*	*	0%	0%
n	79	96	77	75

*complete breakdown of response rates not yet available

Question #8 response	**1998**	**1999**	**2001**	**2002**
A	*	*	34%	47%
B	*	*	55%	43%
C	6%	6%	12%	7%
D	*	*	0%	3%
E	*	*	0%	0%
F			0%	1%
n	79	96	77	75

Although the rate of correct responses is consistently low, the ratio of correct responses on Question #8 to those on Question #1 is remarkably consistent from year to year:

	1998	1999	2001	2002
$\dfrac{\textit{correct responses on } \#8}{\textit{correct responses on } \#1}$	0.43	0.60	0.50	0.50

This certainly suggests that students had more difficulty, for whatever reason, with the question posed in diagrammatic form in comparison to the one posed in verbal form.

As a consistency check, Question #8 along with a question very similar to Question #1 have also been administered post-instruction in the same course. Although correct response rates were dramatically higher on both items, and most of the discrepancy was thereby erased, a small difference persisted. In 2002, the correct post-instruction response rate on Question #1 was 93%, while that on Question #8 was 86%.

Similar matched sets of test items have been administered for other physics concepts. Here I present data for one such set: Quiz #11 (see page 16), which relates to Coulomb's law of electrical force. (Correct Answers: #1, A; #2: A; #3, E; #4, E.)

It is extremely difficult to prepare such matched question sets so that each question on a set is *fully* equivalent to the others; some differences always exist with respect to some details of the information presented. (For example, a vector diagram inevitably makes available the directions of interaction forces; however, including such information in verbal or mathematical form, while possible, is much more cumbersome and would tend to unnecessarily obscure the main idea of the question.) Nonetheless, the four items on the question set shown here are substantially equivalent, and the four representations utilized (verbal, diagrammatic, mathematical/symbolic, and graphical) had all been extensively practiced by the students on quizzes, exams, and homework questions.

An extra-credit option on each test item allows students to increase their score if their response on that particular item is correct. Writing a "3" on the indicated line would increase the item score from 2.5 points for a correct response to 3.0 points. However, selecting this option and providing an *incorrect* response would result in a score of –1.0 for that item, rather than the 0.0 score that would otherwise be earned.

Results for several differing course offerings are shown in the table below. (Numbers shown are fractions of overall responses in each category; "low-conf correct" means "fraction of students who provided correct answer but indicated lower confidence by failure to select extra-credit option.")

The results show that correct response rates for items #1, #2, and #3 were nearly the same, while that for #4 – the graphical representation – was somewhat lower, perhaps due to the relatively unfamiliarity of that representation in the context of this particular question. It is also striking that the proportion of low-confidence correct responses was lower on the question posed in verbal representation than on the other three items, in each of the four years for which results have been analyzed. The overall rate of "low-confidence correct" responses was 15% on the verbal representation, compared to 22% on the other three items. This is certainly not a large discrepancy – it is only marginally statistically significant, if at all – but the fact that it was observed consistently is nonetheless remarkable and worthy of further study.

QUIZ #11	**N**	**#1 incorrect**	***#1 low-conf correct***	**#2 incorrect**	***#2 low-conf correct***	**#3 incorrect**	***#3 low-conf correct***	**#4 incorrect**	***#4 low-conf correct***
1998	71	0.04	*0.06*	0.07	*0.15*	0.10	*0.16*	0.14	*0.16*
1999	91	0.11	*0.12*	0.15	*0.17*	0.18	*0.15*	0.21	*0.15*
2000	79	0.14	*0.22*	0.11	*0.26*	0.10	*0.25*	0.11	*0.30*
2001	75	0.12	*0.21*	0.15	*0.31*	0.13	*0.35*	0.23	*0.28*
MEAN		0.10	*0.15*	0.12	*0.22*	0.13	*0.23*	0.17	*0.22*

V. Conclusion

There is little doubt that the form of representation of physics concepts may have an influence on the ways in which students learn and understand those concepts. Certain representations may pose particular learning difficulties – or, on the other hand, might be particularly fruitful – in the context of particular subject areas. It may also be the case that certain students are relatively more or less successful with particular forms of representations, and it might turn out that the relative utility of different representations varies significantly from one concept to another. The preliminary results presented in this paper suggest that these questions merit substantial addition scrutiny, and our group is continuing to investigate these issues.

Acknowledgments

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I would like to thank Leith Allen for provocative and useful conversations, and Larry Engelhardt for assistance with data analysis.

Physics 112
Quiz #11
October 6, 2000

Name: ______________________

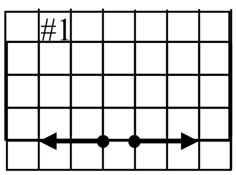
IF YOU WANT A QUESTION GRADED OUT OF THREE POINTS (–1 [MINUS ONE] FOR WRONG ANSWER!!) WRITE "3" IN SPACE PROVIDED ON EACH QUESTION.

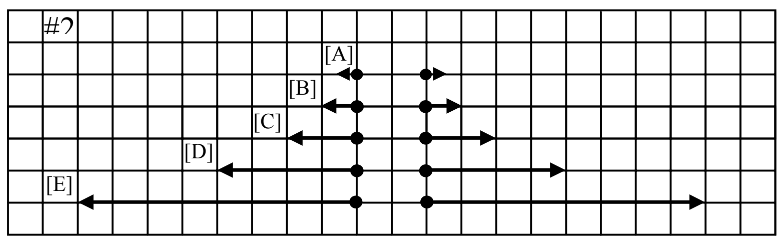
1. When two identical, isolated charges are separated by two centimeters, the magnitude of the force exerted by each charge on the other is eight newtons. If the charges are moved to a separation of eight centimeters, what will be the magnitude of that force now?

A. one-half of a newton
B. two newtons
C. eight newtons
D. thirty-two newtons
E. one hundred twenty-eight newtons

Grade out of three? Write "3" here: ______

2. Figure #1 shows two identical, isolated charges separated by a certain distance. The arrows indicate the forces exerted by each charge on the other. The same charges are shown in Figure #2. Which diagram in Figure #2 would be correct?





A.
B.
C.
D.
E.

Grade out of three? Write "3" here: ______

3. Isolated charges q_1 and q_2 are separated by distance r, and each exerts force F on the other. $q_1^{initial} = q_1^{final}$ and $q_2^{initial} = q_2^{final}$; $r^{initial} = 10m$; $r^{final} = 2m$. $F^{initial} = 25N$; $F^{final} = ?$

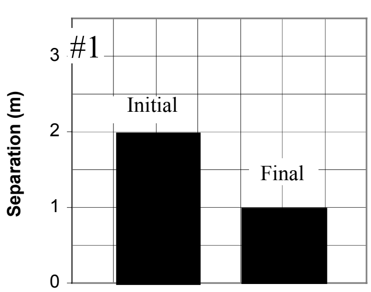
A. 1 N
B. 5 N
C. 25 N
D. 125 N
E. 625 N

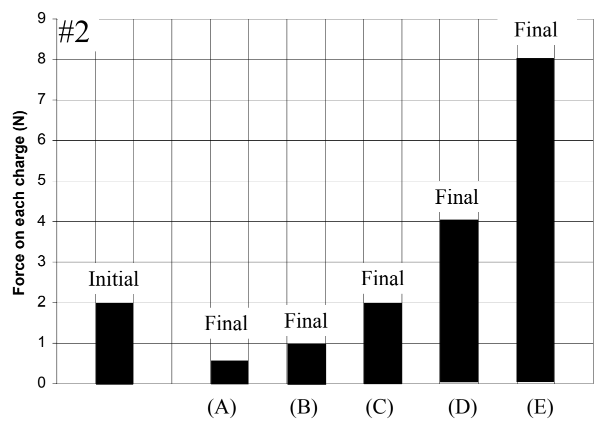
Grade out of three? Write "3" here: ______

4. Graph #1 refers to the initial and final separation between two identical, isolated charges. Graph #2 refers to the initial and final forces exerted by each charge on the other. Which bar is correct?

Grade out of three? Write "3" here: ______

A.
B.
C.
D.
E.





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