Surveying students' conceptual knowledge of electricity and magnetism

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(Received 15 May 2000; accepted 26 October 2000)

The Conceptual Survey of Electricity and Magnetism (CSEM) was developed to assess students' knowledge about topics in electricity and magnetism. The survey is a 32-question, multiple-choice test that can be used as both a pretest and posttest. During four years of testing and refinement, the survey has been given in one form or another to more than 5000 introductory physics students at 30 different institutions. Typical pretest results are that students in calculus-based courses get 31% of the questions correct and student's in algebra/trigonometry-based courses average 25% correct. Posttest correct results only rise to 47% and 44%, respectively. From analysis of student responses, a number of student difficulties in electricity and magnetism are indicated.

[DOI: 10.1119/1.1371296]

I. INTRODUCTION

Over the last 20 years, physics education research has revealed that students already have a number of ideas about how physical systems behave even before they start to study physics.[1–4] In many cases these ideas (often called alternative conceptions or common sense science) differ from accepted scientific ideas. Other research has shown that it is difficult for students to change their initial ideas.[5]

The development and extensive use of the Force Concept Inventory (FCI) conceptual test concerning some basic kinematics and Newton's three laws has raised the consciousness of many physics teachers about the effectiveness of traditional education.[6,7] Many physics instructors have expressed an interest in assessing students' knowledge of electricity and magnetism. However, developing an instrument to assess students' ideas in electricity and magnetism is a very different task than development of the FCI.

II. DEVELOPMENT OF THE CONCEPTUAL SURVEY OF ELECTRICITY AND MAGNETISM (CSEM)

Our initial goal was to develop a primarily qualitative instrument to pretest and posttest students in general physics courses (algebra and calculus-based physics). We wanted to be able to assess students' initial knowledge in electricity and magnetism as well as the effect of various forms of instruction on changing that knowledge base to facilitate comparisons among courses, curricula, and instructional methods. We also wanted to provide an instrument that would touch on important concepts throughout the domain of electricity and magnetism. Most instructors feel that they have limited time to devote to assessing students' knowledge so the numbers, and lengths, of assessments need to be minimized. In contrast to instruments like the FCI, or the Force and Motion Conceptual Evaluation (FMCE) or the Test of Understanding Graphs-Kinematics (TUG-K), the CSEM is a broad survey instrument.

Because of inherent difficulties and practical considerations described later, we did not expect to be able to develop a conceptual inventory for the entire domain of electricity and magnetism. Rather our goal was to develop an instrument which could be useful for getting an overview of students' knowledge. (Actually we would question the idea that there can be anything like a single conceptual inventory for such a broad range of topics.)

Developing a qualitative assessment of students' ideas in electricity and magnetism is a major challenge for a variety of reasons. For one thing the physics education research on students' preinstructional ideas about electricity and magnetism is meager.[2,8–14] In contrast, when the FCI was developed there was substantially more known about students' alternative, or common sense, ideas. Another difference is the focus of the instrument. The FCI focuses on the essential ideas of Newtonian mechanics. Electricity and magnetism is a much broader conceptual area and relies on understanding in other domains such as force, motion, and energy.

Developing an instrument for first semester topics from mechanics, where many students will have some familiarity with the phenomena, language, and concepts involved, contrasts strongly with developing an instrument for electricity and magnetism. In the domain of electricity and magnetism, most students lack familiarity with both the phenomena and most of the concepts, language, principles, and relations. This issue of experience with the phenomena versus formalism (the formal, including the mathematical, expression of the concepts, principles and relations) is important in electricity and magnetism because traditional instruction emphasizes formalism over phenomena. Consequently, decisions about whether to emphasize phenomena or formalism in the questions on an assessment for this domain are complex.

Preliminary work on the development of the Conceptual Survey of Electricity and Magnetism (CSEM) began with work on two separate tests, one for electricity (the CSE—Conceptual Survey of Electricity) and one for magnetism (the CSM—the Conceptual Survey for Magnetism). A con-

I.	Charge distribution on conductors/insulators	1, 2, 13
II.	Coulomb's force law	3, 4, 5
III.	Electric force and field superposition	6, 8, 9
IV.	Force caused by an electric field	10, 11, 12, 15, 19, 20
V.	Work, electric potential, field and force	11, 16, 17, 18, 19, 20
VI.	Induced charge and electric field	13, 14
VII.	Magnetic force	21, 22, 25, 27, 31
VIII.	Magnetic field caused by a current	23, 24, 26, 28
IX.	Magnetic field superposition	23, 28
X.	Faraday's law	29, 30, 31, 32
XI.	Newton's third law	4, 5, 7, 24

Fig. 1. Conceptual areas and question numbers that address each conceptual area for the CSEM.

scious decision was made to exclude the topic of dc circuits from the electricity test because of concern over its length, and there were already some instruments under development for dc circuits.[15,16] A group of experienced college physics professors at a two-year college physics workshop developed lists of major concepts and an initial set of questions for each test. These preliminary tests [called the Electric Concepts Inventory (ECI) and Magnetism Concepts Inventory (MCI) initially[17]]were used in a number of classrooms during the 1995–96 academic year.

Analysis of the results on the preliminary versions and data from administering open-ended versions of the more promising questions led to the beta versions which were administered during the 1996–97 academic year. The open-ended response data also led to changes in the distracters (incorrect answer choices) for a number of questions in the second version. After subsequent analysis and review it was decided to construct one test (the CSEM form D) to survey electricity and magnetism that was a subset of the two separate tests. This test (CSEM) went through three stages of revision (resulting in version G) based on analysis of student data, students' explanations for their responses, and feedback from physics instructors who evaluated and/or administered the CSEM. The topics and corresponding question numbers included on this test are shown in Fig. 1.

III. COMPARING CONCEPTUAL ASSESSMENTS

We believe it is very important to understand the differences between the CSEM and other conceptual assessments that have been developed recently. One of the primary reasons for being aware of the character of each assessment is because interpreting the results of the test depends on what type of conceptual test it is. Conceptual instruments can vary in a number of ways. For example, a test could focus on a small number of concepts, e.g., Newton's laws of motion in the FCI, or it could attempt to survey a much larger conceptual domain, e.g., electricity and magnetism in the CSEM. Tests can have questions which use natural, i.e., everyday, language and situations and have answer choices which closely model students' natural (common sense) beliefs. In contrast, tests can have questions which use technical language and physics situations, such as adding field vectors. In a similar way a test can ask questions that require little formal physics knowledge (most of the questions in the FCI are this type), or ones that demand specific physics knowledge. An example of the latter would be a question asking how the kinetic energy of a particle placed in a uniform electric field will change after the particle is released. Finally, tests can vary in whether the questions concentrate on phenomena, e.g., which way will a compass needle point when placed near a current-carrying wire, or on the formalism, e.g., given equipotential lines, how will field strengths compare. Instructors should be aware of the characteristics of any instrument they use and make sure those characteristics match the goals of their assessment plan.

IV. ANALYSIS OF THE CSEM

There have been several earlier publications about developing conceptual instruments.[6,18] Beichner[19] did a very thorough job of describing the techniques for analyzing a test, so we will include only brief descriptors of the techniques we employed. Aubrecht and Aubrecht[20] have presented guidelines for developing quality multiple-choice items, so we will not discuss that issue.

Version G of the CSEM was subjected to the traditional analysis of both individual items and the overall test. [We report here on version G rather than the most recent version (version H) because it differs from the current version only slightly, and because it is the version for which we have the most complete data that has been analyzed.] The analysis which follows was carried out on posttest results. The presence of common sense ideas as alternate answer options for many items as well as the students' lack of familiarity with a number of the formal terms and ideas resulted in very low pretest scores. Since these overall pretest scores were relatively close to random guessing, despite the presence of definite response patterns on a number of individual questions, using standard test analysis tools on the pretests was not appropriate.

A. Quality of test items

There are two standard measures of the quality of items on a test: difficulty and discrimination. Difficulty is exactly what the name implies, how difficult the item is. It is usually measured by finding the percentage of subjects who get the item correct. The average difficulty ratings (ranging from 0.0 if no one answers correctly to 1.0 if everyone answers correctly) for the items on version G of the CSEM are displayed in Fig. 2.

A difficulty value of 0.5 is usually taken as the ideal, but any real test will have items that range in difficulty. As seen in Fig. 2, the items on the CSEM range in difficulty from about 0.10 to a little over 0.8, which is a reasonable range. However, there are only about seven items with difficulties of 0.6 or larger, and this is probably fewer than would be ideal.

Discrimination is a measure of how well an item differentiates between competent and less competent students. For example, do students scoring in the top 25% of the test as a whole (a measure of competent students) also score higher than less competent students on a particular item? It is typically calculated by subtracting the number of students in the bottom 27% of the overall score range who got the item correct (N_L) from the number of students in the top 27% of

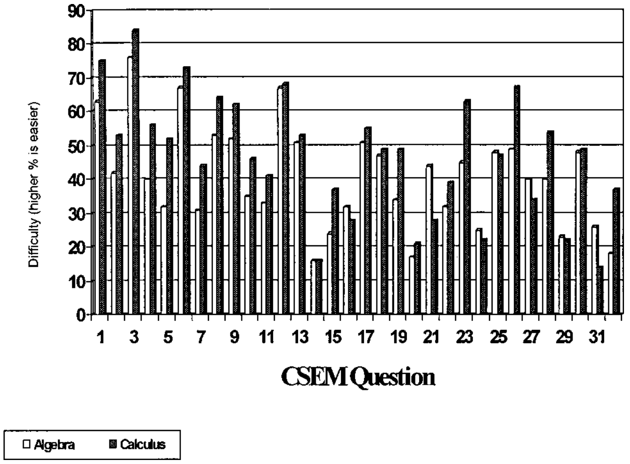


Fig. 2. Difficulty of CSEM, Version G, by question. Overall results for two year and four year algebra and calculus classes.

the score range who got the item correct (N_U) and dividing by half the sum of these two groups $[(N_L+N_U)/2]$. That is,

$$\text{Item discrimination}=\frac{N_U-N_L}{(N_L+N_U)/2}.$$

Discrimination values range from -1.0 to 1.0.

For the items on the CSEM, students in regular calculus-based physics classes had discrimination values ranging from approximately 0.1 to 0.55. While these values are not as high as one would hope, all but four of the items had values greater than 0.2, which is the traditional lower limit for acceptability.

The difficulty of an item has a strong effect on the discrimination of the item. A discrimination value of 1.0 can only be obtained by an item with a difficulty of 0.5. As the difficulty moves away from 0.5, in either direction, the maximum discrimination decreases. Since only 11 of the 32 items on the test had difficulty averages in the 0.4 to 0.6 range, some of the explanation for the relatively small discrimination values may be attributed to the average difficulty of the items.

B. Overall measures of the test

There are two standard overall measures of the quality of a test: validity and reliability. Validity is an estimate of how well the test measures what it contends to measure. There are several different ways to estimate the validity of a test. In evaluating the CSEM we asked 42 two-year college physics professors attending two workshops in two regions of the country to rate each item on a five-point scale (1 being low and 5 being high) for both reasonableness and appropriateness. When evaluating the appropriateness of each item, we ask for a separate response for algebra/trigonometry-based courses and calculus-based courses. The average overall ratings, as well as the ranges and standard deviations, are given in Table I. All of the items on the CSEM were rated as both highly reasonable and appropriate for both courses.

Table I. Validity (reasonableness and appropriateness) of questions on the CSEM, version G.

	Reasonable		Appropriate-Algebra		Appropriate-Calculus	
Question	Mean	SD	Mean	SD	Mean	SD
1	4.62	0.67	4.63	0.60	4.71	0.52
2	4.59	0.68	4.57	0.61	4.74	0.51
3	4.67	0.70	4.76	0.43	4.76	0.50
4	4.72	0.56	4.76	0.43	4.76	0.50
5	4.74	0.50	4.67	0.54	4.73	0.52
6	4.71	0.57	4.60	0.77	4.74	0.51
7	4.72	0.72	4.77	0.43	4.85	0.36
8	4.51	0.72	4.26	0.95	4.74	0.51
9	4.44	0.75	4.20	0.83	4.74	0.57
10	4.69	0.61	4.62	0.65	4.88	0.33
11	4.66	0.71	4.47	0.83	4.73	0.57
12	4.69	0.61	4.74	0.45	4.76	0.44
13	4.67	0.62	4.43	0.92	4.76	0.50
14	4.36	0.99	4.03	1.24	4.50	0.88
15	4.54	0.72	4.51	0.70	4.71	0.46
16	4.38	0.92	4.29	0.91	4.39	0.86
17	4.71	0.61	4.62	0.82	4.82	0.39
18	4.61	0.77	4.36	0.93	4.73	0.45
19	4.56	0.82	4.56	0.70	4.61	0.66
20	4.43	0.83	4.30	0.85	4.56	0.67
21	4.61	0.80	4.64	0.74	4.69	0.66
22	4.49	0.95	4.64	0.63	4.74	0.59
23	4.49	0.95	4.79	0.47	4.79	0.52
24	4.66	0.69	4.51	0.85	4.59	0.85
25	4.63	0.86	4.74	0.55	4.82	0.51
26	4.68	0.79	4.85	0.37	4.82	0.45
27	4.63	0.86	4.64	0.81	4.62	0.85
28	4.68	0.62	4.54	0.80	4.70	0.52
29	4.32	1.06	4.36	0.90	4.54	0.79
30	4.51	0.87	4.41	0.82	4.51	0.68
31	4.35	1.00	4.30	1.02	4.57	0.73
32	4.40	1.13	4.16	1.20	4.66	0.78

The reliability of a test is a measure of how consistently the test will reproduce the same score under the same conditions. On a reliable test, two students who are matched in knowledge and skill will get the same score. In other words equivalent students, either two different students or the same student at two different times, will get the same score on a reliable test. The standard way to calculate the reliability of a test is to use what is called KR 20.[21] This formula gives a representation of the average correlation between the test subdivided into two halves in all possible ways. In other words the actual test is broken down into two tests, each consisting of half of the items, and the correlation is calculated between performance on those two subtests. The actual calculation is given by

$$r_{xx}=\frac{n}{n-1}\left(1-\frac{\Sigma pq}{S_x^2}\right),$$

where n is the number of items in the test, p is the proportion of people who answered an item correctly, q is the proportion of people who answered the item incorrectly, and S_x^2 is the variance of the whole test. This calculation underestimates the reliability of the test.

Reliability values for tests run between 0 and 1.0. Reliabilities in the range 0.9 to 1.0 are rare. Values in the range 0.8 to 0.9 are very high and indicate a test that can be used for both individual and group evaluation. Values in the range 0.7 to 0.8 are common for well-made cognitive tests. Values in the range 0.6 to 0.7 are considered weak for cognitive tests, but are acceptable for personality tests. A range of 0.5 to 0.6 is common for *well-made* classroom tests. The KR 20 posttest estimates for the CSEM are around 0.75, which is a very reasonable value.

We ran other evaluations of the CSEM, including a factor analysis. (What we actually calculated was a principal components analysis, which is a form of factor analysis.) A factor

Table II. Overall results on CSEM.

Course	Pretest	(Standard deviation)	n	Posttest	(Standard deviation)	n
Algebra	25%	(8%)	273	44%	(13%)	262
Calculus	31%	(10%)	1213	47%	(16%)	1030
Honors-Calc	41%	(21%)	99	69%	(14%)	145
Majors/Grad				70%	(17%)	24
Overall results on CSE						
Algebra	23%	(12%)	220	42%	(15%)	273
Calculus	35%	(14%)	439	47%	(16%)	736
Overall results on CSM						
Algebra	15%	(9%)	253	39%	(15%)	289
Calculus	21%	(12%)	389	47%	(18%)	372

analysis calculates the correlation among all of the items on the test and then looks for significantly correlated groups of items. One then looks for some quantity or aspect of the entities being measured that could explain the correlation among the items in the group. For a test to have identifiable factors there usually needs to be multiple questions on the same concept or principle which could then correlate with each other. On the CSEM, no strong factors were identified. There were 11 factors identified with eigenvalues greater than one (one basis for deciding on legitimate factors), but that number is clearly too large to be a useful reduction from 32, and the largest of these factors accounted for only 16% of the variance. This latter figure is very small for a first factor, so these 11 factors, while mathematically identifiable, are not meaningful. The factor structure of the test could be improved but that would require adding additional questions, increasing the length of the test and the time to use it.

Overall the results of this analysis of this survey instrument indicate that the CSEM is a valid, reliable instrument. The test is a combination of questions probing students' alternative conceptions and questions that are more realistically described as measuring students' knowledge of aspects of the formalism. With the information currently available about students' natural ideas in these domains, any survey of the domain as a whole is likely to have this character.

V. STUDENT RESULTS

A. Overall results

The overall results on the CSEM for two groups of students, those enrolled in algebra/trigonometry-based courses and those enrolled in calculus-based courses, can be found in Table II. Table II has overall results (not broken up by type of institution) since there were no significant differences between results for courses taught at two-year colleges, four-year colleges, or universities. All results are for unmatched data sets since the overall student responses for matched student data were essentially the same as student responses for unmatched data.

As might be expected, the overall pretest scores are very weak, being barely above random choice for the algebra students. (Although the students are not responding randomly to the individual questions as will be shown below.) These results are probably to be expected because of the students' lack of familiarity with the phenomena and the formalism, as well as lingering difficulties with important concepts and ideas from first semester.[10] What is not expected is the poor performance on the posttest. A class average of around 50% on a test composed of questions that experienced physics teachers agree are reasonable and appropriate is definitely disappointing. Also included in Table II are the results on the CSE and CSM surveys for the same types of students. The pretest and posttest results are less than the CSEM results for the algebra/trigonometry-based students. The pretest results are higher for the CSE and lower for the CSM surveys for the calculus-based students, but are essentially the same on the posttests.

Three other sets of data were also collected. Both pretest and posttest data from two high school classes ($n=103$) were collected. These high school students scored 23% on the pretest and 49% for the posttest and these results are very similar to the values for the college classes. Additionally, posttest data from two honors calculus-based engineering physics courses at a large research university were collected. This course employed an interactive engagement approach. This honors data is shown at the bottom of the CSEM data in Table II. Clearly the honor classes performed better, as one would expect. A posttest average of approximately 70% is reasonable since a mixed group of physics majors and graduate students also had an average of 70% as shown in Table II. These results, especially when coupled with the result from slightly earlier versions—forms E and F [a 77% average ($n=95$)] for several groups of two-year college physics professors who attended several of the Two-Year College Workshop project sessions indicate that the test is a viable measure of learning in this domain. (This faculty average is comparable to the 79% and 80% scores on the CSE and CSM surveys for two-year college physics professors, $n=188$ and $n=118$, respectively.)

We can see the comparison of the question responses for the CSEM by looking at Fig. 2 again. One noticeable result from Fig. 2 is the disparity between the results on electricity questions (questions 1–20) and magnetism questions (questions 21–32). On the pretest, the calculus students performed 16% poorer (algebra-based students 14% poorer) on the magnetism questions compared to the electricity questions. Even on the posttest, students scored 12% (calculus-based) and 6% (algebra-based) lower on the magnetism questions versus the electricity questions. This disparity of results is comparable, although slightly higher, than student results on the pretest and posttest on the CSE and CSM surveys as well (see Table II).

B. Detailed results

Specific question results for the CSEM (form G) are indicated in Table III. (Starred questions in the table indicate items which have been revised in form H.) The column labeled *n* represents the number of students who have answered this question on one of the CSE, CSM, or CSEM surveys. We have combined results from the different surveys because there were no significant differences in response patterns wherever the items were presented. The numbers vary because certain questions have appeared on all seven versions of the instruments while others have been more recent. The answer columns display the percentages of students who answered the question with that letter response.

1. Conductors and insulators

Students seem to have some confusion about how charges are distributed on conductors and insulators. On the pretest there is a clear difference in how the students respond to questions 1 and 2. For question 1 about conductors the majority of the students distribute the charges over the sphere (choices B and C). In contrast, the answer distribution on question 2 is essentially random, which is what we would expect if the students did not have any strong initial ideas.

Student response to question 1 about charge distribution on conductors shows a definite improvement from pre- to posttest (gains of 24%) and a good success rate on the posttest (63% and 75%). However, at post instruction a substantial number of students still responded that the charge was distributed over both the inner and outer surfaces of the metal sphere (14% to 23%). For charge distribution on insulators, see question 2, the gains were less (about 15%) and the posttest results were a little more than 20% less than question 1. It appears that a substantial number of students seem not to be able to distinguish between conductors (answers B and C) and insulators or fully understand what happens to the charge at all (answer E). The data suggests that many of the students may simply be recalling a statement about charge distribution without understanding the physical mechanism.

Based on results to date, students' knowledge of the shielding effect of conductors seems rather weak. The contrast between about 50% correct on question 13 and about 16% correct on question 14 may seem strange. However, part of the explanation is that about half of the students chose the correct response on question 13 for the wrong reason. In version G the sphere in question 13 was initially uncharged. (This has been changed on version H.) From open-ended responses, it appeared that these students believe the field within is zero because the sphere was initially uncharged. This also helps explain why E is a strong pretest choice. For question 14 there is a clear pattern in the pretest choices and more than 50% of the students still choose answer A for question 14 on the posttest, which seems to indicate a misuse of Newton's third law.

2. Coulomb's law

Question 3, which is a straightforward application of Coulomb's law, is the easiest item overall, having the best pretest and posttest correct answer percentages. However, when we turn to question 4, which looks at the force on the other charge, we find many fewer correct responses (about 33% less). The favored alternative choice C indicates that many students do not apply Newton's third law or symmetry of Coulomb's law to electric point charge situations. Students still seem to believe larger ''objects'' (in charge magnitude for this case) exert larger forces than smaller ''objects.'' Question 5 shows an additional small reduction in correct responses and indicates confusion on both the effect of the magnitude of the charges and the distance of separation. In general, students do not seem to be able to apply Coulomb's law as well as one would expect after instruction.

3. Force and field superposition

Students seem to perform superposition fairly well for straightforward applications. Question 6 has a good success rate for both groups of students on the posttest and is the best gainer from pretest to posttest of the electricity questions for the algebra-based students. Questions 8 and 9 are a more subtle application of superposition coupled with force and field ideas. Students perform about 10% less well on the posttest for these questions than on question 6. A noticeable percentage of students seem to be confused about how a new charge affects the direction of the force or field, answer D.

Question 23 is designed to be a straightforward application for the magnetic field around a long, straight wire and superposition. Although students may not know this idea on the pretest, we would assume they would know it on the posttest. Choice B is a fairly strong distracter and may indicate that students confuse the magnetic field effects with electric field effects (if the wires were positive and negative). Combined with answer C, which could also fall under this interpretation, about 20% of the calculus-based students and 28% of the algebra-based students seem to have this idea on the posttest. Answer E was a distracter on the pretest, but not on the posttest. Answer D could be interpreted as the opposite of the correct answer, A. It, however, does not receive much support. This question was one of the best gainers.

Question 26 provides some insight into the ''depth'' of student understanding of the magnetic field created by a current carrying wire and superposition of these fields. This straightforward question does have a high success as a posttest item, 67% for calculus-based students and 49% for algebra-based students (it is the best performer for magnetism questions). This question shows a clear nonrandom response pattern on the pretest. Answer B is an attractive distracter for pretest students. This answer probably still indicates electric field thinking by students with the current coming out of the page equated to a negative charge consistent with answer B of question 23. (On the posttest this distracter becomes insignificant.) Answer D remains a fairly good distracter for both pretest and to a lesser extent for the posttest (except for algebra-based students). This could indicate that students think the current coming out of the page is a positive charge (electrical analog). This question is the best gainer of all the CSEM questions, hopefully indicating that students can be helped to abandon the electric charge analogy when determining magnetic fields for electric currents.

Question 28 is another superposition question. Students show a fairly strong understanding of superposition by choosing answer C. Answer A would be a reasonable alternative if their only problem was getting the direction wrong, but it is an insignificant distracter. Answer E, a strong distracter, may be another electrical analog with two like charges and the point in between them having no net field.

4. Force, field, work, and electric potential

Influence of residual conceptual problems from first semester could help explain the weak performance on question 10. Post instruction, one would expect students should have

Table III. Student responses for CSEM questions (A=algebra-based students, C=calculus-based students).

Question		*n*		A (%)		B (%)		C (%)		D (%)		E (%)		Correct answer
		A	C	A	C	A	C	A	C	A	C	A	C	
1	Pretest	380	1456	5	4	**39**	**51**	30	30	14	10	7	3	B
	Posttest	425	1332	4	2	**63**	**75**	23	14	7	5	3	2	
2	Pretest	380	1456	**27**	**39**	16	17	11	8	14	11	26	24	A
	Posttest	425	1332	**42**	**53**	21	15	5	6	11	14	19	11	
3	Pretest	302	1314	4	4	**60**	**74**	16	9	9	6	1	2	B
	Posttest	354	1151	5	4	**76**	**84**	9	6	8	4	0	0	
4	Pretest	302	1314	7	3	**38**	**44**	27	30	16	18	1	2	B
	Posttest	354	1151	5	2	**40**	**56**	32	29	21	12	2	1	
5	Pretest	302	1314	8	14	17	13	**21**	**39**	34	20	7	10	C
	Posttest	354	1151	14	16	20	11	**32**	**52**	22	14	11	4	
6	Pretest	176	870	8	10	16	11	24	13	18	5	**34**	**61**	E
	Posttest	168	435	7	7	13	9	10	7	4	4	**67**	**73**	
7	Pretest	380	1456	25	17	**14**	**25**	39	48	8	6	5	2	B
	Posttest	425	1332	19	11	**31**	**44**	42	38	5	3	2	3	
8	Pretest	425	1645	6	3	**32**	**51**	18	12	22	24	9	7	B
	Posttest	465	1778	5	4	**53**	**64**	10	11	21	14	8	5	
9	Pretest	425	1645	7	7	**36**	**48**	19	16	17	18	6	6	B
	Posttest	465	1778	10	6	**52**	**62**	12	11	16	13	5	4	
10	Pretest	425	1645	10	6	17	18	**16**	**24**	9	12	36	36	C
	Posttest	465	1778	6	7	20	24	**35**	**46**	12	10	25	12	
11	Pretest	425	1645	34	32	17	22	11	13	11	11	**13**	**18**	E
	Posttest	465	1778	30	19	14	13	13	15	9	10	**33**	**41**	
12	Pretest	425	1645	15	15	10	12	7	7	**52**	**60**	3	4	D
	Posttest	465	1778	9	8	8	13	13	7	**67**	**68**	2	1	
13*	Pretest	176	870	15	16	31	39	2	4	2	2	**47**	**36**	E
	Posttest	168	435	27	23	20	19	1	3	0	2	**51**	**53**	
14	Pretest	380	1456	49	54	10	8	7	5	**5**	**8**	12	19	D
	Posttest	425	1332	54	50	9	13	4	6	**16**	**16**	13	14	
15	Pretest	302	1314	**13**	**17**	25	19	35	52	5	4	9	5	A
	Posttest	354	1151	**24**	**37**	24	22	34	34	9	3	8	3	
16	Pretest	386	1645	10	13	19	20	12	17	20	20	**19**	**25**	E
	Posttest	432	1778	13	15	22	23	13	14	17	12	**32**	**28**	
17	Pretest	380	1456	4	5	18	17	31	35	5	8	**25**	**28**	E
	Posttest	425	1332	2	2	16	14	23	23	6	6	**51**	**55**	
18	Pretest	380	1456	4	2	7	8	21	22	**29**	**41**	22	21	D
	Posttest	425	1332	2	1	4	4	17	13	**47**	**49**	28	32	
19	Pretest	380	1456	**13**	**22**	18	24	23	23	12	12	13	12	A
	Posttest	425	1332	**34**	**49**	25	24	14	12	11	6	10	8	
20	Pretest	380	1456	23	22	18	24	22	28	**9**	**13**	6	4	D
	Posttest	425	132	18	14	20	25	32	34	**17**	**21**	8	4	
21	Pretest	419	1564	17	19	19	31	13	12	6	8	**31**	**26**	E
	Posttest	444	1287	15	18	8	28	21	17	8	8	**44**	**28**	
22	Pretest	419	1564	34	35	10	17	12	12	**7**	**16**	26	16	D
	Posttest	444	1287	22	14	11	14	28	30	**32**	**39**	4	2	
23	Pretest	411	1405	**11**	**20**	32	30	21	20	8	8	15	17	A
	Posttest	444	1263	**45**	**63**	15	10	13	10	9	8	11	7	
24	Pretest	419	1564	3	4	45	48	**8**	**7**	20	29	14	8	C
	Posttest	444	1287	2	1	45	45	**25**	**22**	19	23	8	7	
25	Pretest	411	1405	14	14	28	22	31	42	**8**	**12**	7	5	D
	Posttest	444	1263	11	8	12	11	20	25	**48**	**47**	5	8	
26	Pretest	411	1405	**8**	**22**	41	30	8	11	24	26	3	6	A
	Posttest	444	1263	**49**	**67**	11	8	6	8	21	12	6	4	
27*	Pretest	322	1298	9	15	14	14	9	8	21	28	**32**	**31**	E
	Posttest	358	1113	19	30	5	8	8	8	23	20	**40**	**34**	
28	Pretest	419	1564	7	8	22	20	**12**	**28**	7	5	38	35	C
	Posttest	444	1426	8	6	12	6	**40**	**54**	3	2	35	30	
29	Pretest	322	1298	25	29	14	18	**9**	**16**	22	23	9	7	C
	Posttest	358	1113	26	21	23	29	**23**	**22**	19	22	6	5	
30	Pretest	322	1298	**25**	**28**	9	13	23	28	15	15	8	11	A
	Posttest	358	1113	**48**	**49**	7	9	15	14	14	14	9	10	
31	Pretest	166	1219	15	12	25	25	43	37	12	16	**4**	**6**	E
	Posttest	159	1036	18	18	15	20	25	29	17	16	**26**	**14**	
32*	Pretest	166	1219	23	16	43	26	12	19	**14**	**29**	5	3	D
	Posttest	159	1036	23	23	40	21	16	12	**18**	**37**	1	4	

little problem thinking through the steps from a uniform field to a uniform force to a uniform acceleration. Evidence that the first step in this reasoning is straightforward is shown by the strong success rate on question 12. However, the fact that about 25% of the students choose B on question 10 indicates that these students may still be associating a constant velocity with a constant force. The open-ended response forms indicated a surprising rationale for choice E on question 10; indications are that these students are working with an idea about an ''equilibrium'' situation in a uniform field. This inference is strengthened by the fact that about 25% of the students choose A on question 11.

Students do not seem to be able to deduce the direction of the electric field from a change in potential. Students seem to confuse whether an increase or a decrease in potential determines direction. On question 20, almost 40% choose an increase, answers A and B, but only 25% on question 19, answer B. A little more than 50% choose a decrease, answers C and D, on question 20, but less than 50% on question 19, answer A. Around 20% of the students choose an answer on question 19 (C and D) that indicates both directions. The field strength seems also to be confusing for many students. Answers A and C on question 20 seem to indicate that students are associating large distances between equipotential lines with stronger field. This distance separation seems to have affected student responses on question 17 as well. Ignoring the change in potential, students choose C more than 20% of the time (for greater distance) and answer B about 16% of the time (for shorter distance).

5. Magnetic force

The poor performance on question 21 will come as no surprise to any experienced physics instructor. We know that students expect a magnetic force whenever an electric charge is placed in a magnetic field. Getting students to first check to make sure the charge has a velocity with at least a component perpendicular to the field direction is very difficult. The first three choices in this question all received about the same interest (about 16% of the responses). Choice D, which is the correct answer if the charge actually were to experience a magnetic force, is the only answer not often chosen.

There are a variety of ways that students seem to be interpreting the effect of a magnetic field on a moving charged particle. On question 22, about $\frac{1}{3}$ of the students choose answer C and about $\frac{1}{3}$ choose answer D. These answers seem to indicate direction confusion. However, there is a strong indication (about 30% of the answers) that students confuse the electric force and magnetic force—see answers A and B. On question 25, a strong alternative answer is C and could indicate a fluid flow interpretation of the effect of the magnetic field on the moving charged particle.

6. Faraday's law

Questions 29 through 32 deal with Faraday's law and magnetic induction. Answers A, B, and C of question 29 imply that the students know that a moving magnetic field (due to the moving magnet) or a moving bulb in a stationary magnetic field will create an induced current (lighting the bulb). Answer B, a powerful distracter, could indicate that students think this is the ''only'' way to get the bulb to light. Answer A, a powerful distracter as well, indicates that students believe a rotation is the ''movement'' necessary to induce a current (as well as moving of the magnetic field source). Answer D, another powerful distracter as well, is puzzling since it implies a moving bulb will create an induced current but not case I. Overall, 72% of the calculus- and algebra-based students chose answers that used the idea that ''motion'' from either the loop or the magnet is necessary to create an induced current. Students may not see the collapsing loop as changing the magnetic flux or the rotating loops as not changing the magnetic flux.

Question 30 approaches the induced current/voltage issue from a different direction. Cases I and II are correct (answer A) but are contained in part in answers A–D. Answers A, B, and D include case I and answers A, C, and D contain case II. Case III is included in answers B, C, and D. It appears that students understand that the current-carrying wire is generating a magnetic field (except possibly those answering E). Students are unsure of what loop motion induces a current. Case III seems to give them trouble determining whether it has an induced current or not. This question is a good gainer.

Question 31 is the least correct question by calculus-based students on the posttest and pretest. It is the most often missed question by algebra-based students on the pretest, but surprisingly not on the posttest. Answers D and E could indicate students think there is an induced ''emf'' that causes charges to move to the top (or bottom) of the metal bar. Unfortunately, these answers account for only 30% of the calculus-based students and 43% of the algebra-based students on the posttest. Answers B and C are strong distracters, possibly indicating those students again think of the electrical effects instead of the magnetic effects. This interpretation would account for 49% of the calculus-based students and 40% of the algebra-based students on the posttest. Answer A also remains a strong distracter and may indicate that students think there is no effect or that there are no charges available to move.

Question 32 investigates an induced voltage experiment. Answer A, a strong distracter, is the same as the ammeter reading versus time graph, indicating the student may believe that the induced voltage is the same (graphically) as the original current. Answer B, a strong distracter and the dominant answer for algebra-based students, is like ''flipping over'' the current graph. Students may be thinking the ''negative'' idea (like question 29). Answer C, a distracter, is more like the ''opposite'' slopes—if current is changing, voltage is not and vice versa. (Answer choices C and E for this question have been revised in version H.)

7. Newton's third law

The failure to believe that Newton's third law extends to electric and magnetic situations is shown by the responses on questions 7 and 24. On question 7 only about 40%, overall, choose the response consistent with Newton's third law. A similar number of students respond that the larger magnitude charge exerts the larger force. A lesser distracter was the smaller magnitude charge exerts the larger force, answer A. When we turn to magnetic interactions we find the same Newton's third law difficulty. On question 24, 22% of the calculus students and 25% of the algebra students applied Newton's third law correctly to the situation. If we include the students who said the magnitudes were equal but had the wrong direction for the interaction, the correct responses increase to 45% and 44%. This still leaves the majority of students not using the third law. About 45% of both the calculus-based and algebra-based students (on both the pretest and posttest) thought the larger current wire exerted a larger force on the other wire, answer B.

VI. DISCUSSION

Our goals when we started this project were to develop a qualitative test that could be used both as a pretest and a posttest in introductory college physics courses and to get some idea of the prevalence of students' ideas before and after instruction. We believe we have accomplished both goals.

The recurrent patterns found in the pretest responses for both groups of students indicate that students are not responding randomly to the questions. Whether the ideas the students are expressing are common-sense conceptions in the same sense as the ''motion implies force'' conception will require much more research. What is clear is that the students are getting ideas from somewhere, perhaps terms and phrases they have heard without really understanding them, and that they are trying to use those ideas. It is also clear that there are some questions for which students retain their initial ideas in the face of instruction, and that there are some questions on which the students switch their responses, but often from one incorrect response to another, rather than from incorrect to correct.

One very strong result from this research is that the postinstruction performance of students on this instrument is much poorer than any instructor would hope. The fact that performance by honors students, graduate/upper level students, and two-year college faculty shows a steady progression indicates that the instrument does measure some aspect of learning in this domain. Against this background the weak overall performance of the students in introductory physics is definitely disappointing.

Examination of the CSEM in the Appendix will show that it has a combination of questions about the basic phenomena in this domain and about the formalism. In mechanics there is a much tighter linkage between phenomena and formalism. In addition, students usually have much more familiarity with the phenomena in mechanics than they do with phenomena in electricity and magnetism. Examination of most general physics textbooks shows that the main focus of the presentation is the formalism. One might wonder how well students can learn a formalism which is designed to explain phenomena with which they have little familiarity and understanding.

Another issue that figures strongly in the CSEM is language. Language is a factor in several ways. First, there is the matter of natural (i.e., everyday) language versus formal (i.e., physics) language. Many of the questions in the CSEM use physics terms because it would be difficult, if not impossible, to ask about the concept or issue without those terms. Consequently, it is difficult to know how students actually interpret the questions on the pretest. Second, even when natural language is being employed the students may not interpret the terms in the same way we do.[22] Third, different instructors often introduce and use the same terms in slightly different ways that may influence how their students interpret a question. All of these aspects mean that interpreting the results on the CSEM should be done with great caution.

Figure 3 indicates the pretest and posttest results on the CSEM for classes that have taken both the pretest and the posttest. The bottom line in Fig. 3 indicates a ''fractional gain''[23] of 15% from pretest to posttest on the CSEM. The middle line and top line indicate ''fractional gains'' of 40% and 60%, respectively. The figure indicates a ''clustering'' of classes in the range between fractional gains of 0.15 and 0.40. This performance implies that additional research on instructional strategies needs to be done before the impact of particular techniques on student performance will be known.

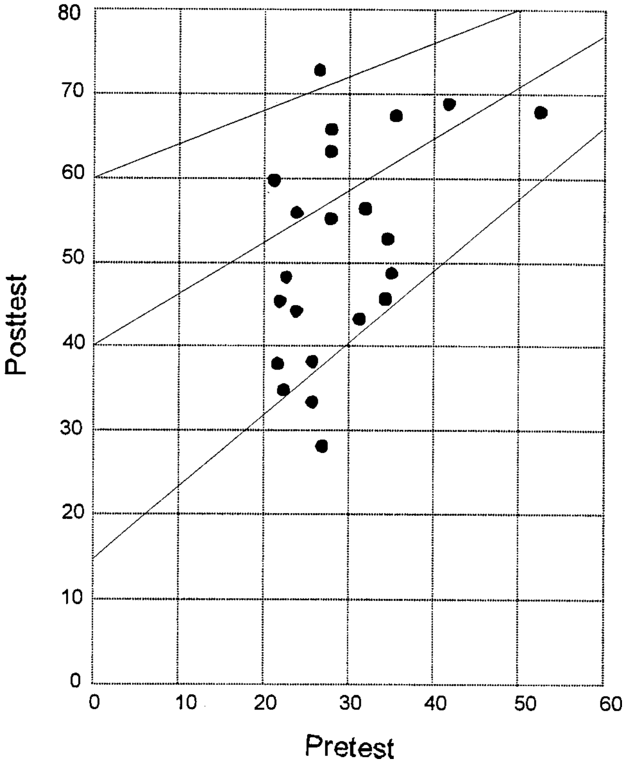


Fig. 3. Posttest versus pretest for CSEM, Version G. Results by class.

VII. SUMMARY

The CSEM is a broad survey of students' knowledge bases in electricity and magnetism. It is a combination of a test of alternative conceptions and knowledge because we are not in a position at this time to develop a test of alternative conceptions alone. We do not have sufficient documented information about the nature of students' alternative, or common sense, ideas about topics in electricity and magnetism. Having said that, the CSEM can provide an estimate of student learning for some of the more important ideas in electricity and magnetism. We hope the CSEM can begin to provide some guidance for research directions into students' common sense conceptions in this domain. It has a combination of questions that probe students conceptual changes as well as questions that determine how well students develop understanding of the important terms and relations. It also has a combination of questions about the phenomena of electricity and magnetism and questions about the physical formalism explaining the phenomena.

In this article we have provided some base-line performance data that we hope will inspire others to develop new and improved ways to teach electricity and magnetism.

ACKNOWLEDGMENTS

This work was supported in part by the Division of Undergraduate Education of the National Science Foundation through a series of grants to the Two-Year College Physics Workshop Project.

We thank Myra West, Marie Plumb, Marvin Nelson, Dwain Desbien, and Mark Bunge for their help in developing the first draft of the instruments for E & M. Several questions in those instruments were modeled on questions initially written by Dennis Albers and we thank him for allowing us to use his materials. We thank the many professors who administered the CSEM and provided us with data and excellent comments. We also want to thank the many participants of the TYC Physics Workshop Project who provided expert comments at various stages of development of the surveys. We thank Robert Beichner and the other members of the North Carolina State University physics education research group for extensive feedback on a preliminary draft of this article. Finally we thank Bruce Sherwood and Ruth Chabay for allowing us to incorporate into the CSEM questions 3, 4, 5, 31, and 32, which they developed.

Appendix

Conceptual Survey in Electricity and Magnetism (CSEM)
(Form H)

(Answer key is the same as Form G)

In any question referring to current, conventional current will be used (where conventional current is the flow of positive charges). In addition, all effects due to the earth's magnetic field will be so small that they will be ignored. Note that the term "particle" is meant to be an object without size or structure.

1. A hollow metal sphere is electrically neutral (no excess charge). A small amount of negative charge is suddenly placed at one point P on this metal sphere. If we check on this excess negative charge a few seconds later we will find one of the following possibilities:
   (a) All of the excess charge remains right around P.
   (b) The excess charge has distributed itself evenly over the outside surface of the sphere.
   (c) The excess charge is evenly distributed over the inside and outside surface.
   (d) Most of the charge is still at point P, but some will have spread over the sphere.
   (e) There will be no excess charge left.

2. A hollow sphere made out of electrically insulating material is electrically neutral (no excess charge). A small amount of negative charge is suddenly placed at one point P on the outside of this sphere. If we check on this excess negative charge a few seconds later we will find one of the following possibilities:
   (a) All of the excess charge remains right around P.
   (b) The excess charge has distributed itself evenly over the outside surface of the sphere.
   (c) The excess charge is evenly distributed over the inside and outside surface.
   (d) Most of the charge is still at point P, but some will have spread over the sphere.
   (e) There will be no excess charge left.

For questions 3 -5:
Two small objects each with a net charge of +Q exert a force of magnitude F on each other.

We replace one of the objects with another whose net charge is +4Q:

3. The original magnitude of the force on the +Q charge was F; what is the magnitude of the force on the +Q now?

   (a) 16F (b) 4F (c) F (d) F/4 (e) other

4. What is the magnitude of the force on the +4Q charge?

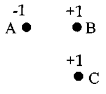
   (a) 16F (b) 4F (c) F (d) F/4 (e) other

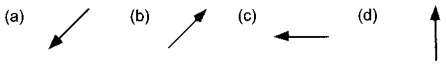
Next we move the +Q and +4Q charges to be 3 times as far apart as they were:

5. Now what is the magnitude of the force on the +4Q?

   (a) F/9 (b) F/3 (c) 4F/9 (d) 4F/3 (e) other

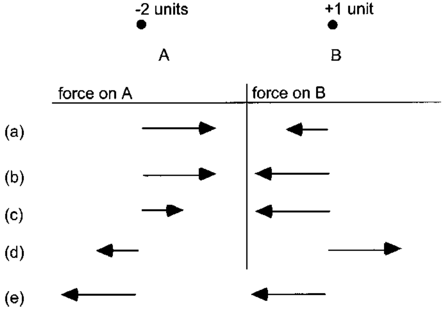
6. Which of the arrows is in the direction of the net force on charge B?





(e) none of these

7. The picture below shows a particle (labeled B) which has a net electric charge of +1 unit. Several centimeters to the left is another particle (labeled A) which has a net charge of -2 units. Choose the pair of force vectors (the arrows) that correctly compare the electric force on A (caused by B) with the electric force on B (caused by A).



8. In the figure below, positive charges q_2 and q_3 exert on charge q_1 a net electric force that points along the +x axis. If a positive charge Q is added at (b,0), what now will happen to the force on q_1? (All charges are fixed at their locations.)

   (a) No change in the size of the net force since Q is on the x-axis.
   (b) The size of the net force will change but not the direction.
   (c) The net force will decrease and the direction may change because of the interaction between Q and the positive charges q_2 and q_3.
   (d) The net force will increase and the direction may change because of the interaction between Q and the positive charges q_2 and q_3.
   (e) Cannot determine without knowing the magnitude of q_1 and/or Q.

9. In the figure below, the electric field at point P is directed upward along the y-axis. If a negative charge -Q is added at a point on the positive y-axis, what happens to the field at P? (All of the charges are fixed in position.)

   (a) Nothing since -Q is on the y-axis.
   (b) Strength will increase because -Q is negative.
   (c) Strength will decrease and direction may change because of the interactions between -Q and the two negative q's.
   (d) Strength will increase and direction may change because of the interactions between -Q and the two negative q's.
   (e) Cannot determine without knowing the forces -Q exerts on the two negative q's.

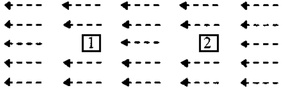
FOR QUESTIONS 10-11

A positive charge is placed at rest at the center of a region of space in which there is a uniform, three-dimensional electric field. (A uniform field is one whose strength and direction are the same at all points within the *region.*)

10. When the positive charge is released from rest in the uniform electric field, what will its subsequent motion be?
    (a) It will move at a constant speed.
    (b) It will move at a constant velocity.
    (c) It will move at a constant acceleration.
    (d) It will move with a linearly changing acceleration.
    (e) It will remain at rest in its initial position.

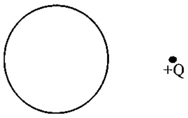
11. What happens to the electric potential energy of the positive charge, after the charge is released from rest in the uniform electric field?
    (a) It will remain constant because the electric field is uniform.
    (b) It will remain constant because the charge remains at rest.
    (c) It will increase because the charge will move in the direction of the electric field.
    (d) It will decrease because the charge will move in the opposite direction of the electric field.
    (e) It will decrease because the charge will move in the direction of the electric field.

12. A positive charge might be placed at one of two different locations in a region where there is a uniform electric field, as shown below.



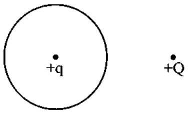
How do the electric forces on the charge at positions 1 and 2 compare?
(a) Force on the charge is greater at 1.
(b) Force on the charge is greater at 2.
(c) Force at both positions is zero.
(d) Force at both positions is the same but not zero.
(e) Force at both positions has the same magnitude but is in opposite directions.

13. The figure below shows a hollow conducting metal sphere which was given initially an evenly distributed positive (+) charge on its surface. Then a positive charge +Q was brought up near the sphere as shown. What is the direction of the electric field at the center of the sphere after the positive charge +Q is brought up near the sphere?



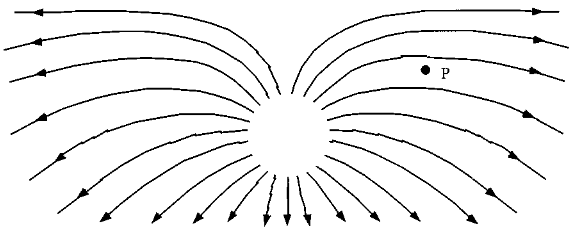
(a) Left
(b) Right
(c) Up
(d) Down
(e) Zero field

14. The figure below shows an electric charge q located at the center of a hollow uncharged conducting metal sphere. Outside the sphere is a second charge Q. Both charges are positive. Choose the description below that describes the net electrical forces on each charge in this situation.



(a) Both charges experience the same net force directed away from each other.
(b) No net force is experienced by either charge.
(c) There is no force on Q but a net force on q.
(d) There is no force on q but a net force on Q.
(e) Both charges experience a net force but they are different from each other.

USE THE FOLLOWING ELECTRIC FIELD DIAGRAM FOR QUESTION 15.



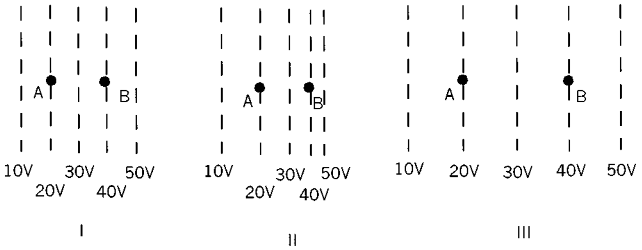
15. What is the direction of the electric force on a negative charge at point P in the diagram above?

(a) ← (b) ↙ (c) → (d) ↗ (e) the force is zero

16. An electron is placed at a position on the x-axis where the electric potential is + 10 V. Which idea below best describes the future motion of the electron?
(a) The electron will move left (-x) since it is negatively charged.
(b) The electron will move right (+x) since it is negatively charged.
(c) The electron will move left (-x) since the potential is positive.
(d) The electron will move right (+x) since the potential is positive.
(e) The motion cannot be predicted with the information given.

FOR QUESTIONS 17-19

In the figures below, the dotted lines show the equipotential lines of electric fields. (A charge moving along a line of equal potential would have a constant electric potential energy.) A charged object is moved directly from point A to point B. The charge on the object is +1 μC.



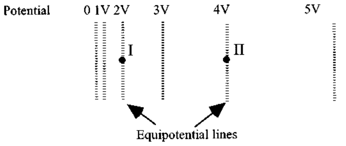
17. How does the amount of work needed to move this charge compare for these three cases?
(a) Most work required in I.
(b) Most work required in II.
(c) Most work required in III.
(d) I and II require the same amount of work but less than III.
(e) All three would require the same amount of work.

18. How does the magnitude of the electric field at B compare for these three cases?
(a) I > III > II
(b) I > II > III
(c) III > I > II
(d) II > I > III
(e) I = II = III

19. For case III what is the direction of the electric force exerted by the field on the + 1 μC charged object when at A and when at B?
(a) left at A and left at B
(b) right at A and right at B
(c) left at A and right at B
(d) right at A and left at B
(e) no electric force at either.

20. A positively-charged proton is first placed at rest at position I and then later at position II in a region whose electric potential (voltage) is described by the equipotential lines. Which set of arrows on the left below best describes the relative magnitudes and directions of the electric force exerted on the proton when at position I or II?

	Force at I	Force at II
(a)	→	⟶
(b)	⟶	→
(c)	←	⟵
(d)	⟵	←
(e)	0	0

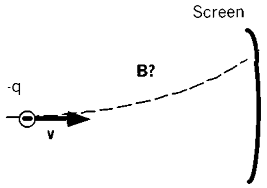


21. What happens to a positive charge that is placed at rest in a uniform magnetic field? (A uniform field is one whose strength and direction are the same at all points.)

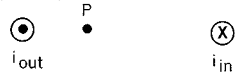
(a) It moves with a constant velocity since the force has a constant magnitude.
(b) It moves with a constant acceleration since the force has a constant magnitude.
(c) It moves in a circle at a constant speed since the force is always perpendicular to the velocity.
(d) It accelerates in a circle since the force is always perpendicular to the velocity.
(e) It remains at rest since the force and the initial velocity are zero.

22. An electron moves horizontally toward a screen. The electron moves along the path that is shown because of a magnetic force caused by a magnetic field. In what direction does that magnetic field point?

(a) Toward the top of the page
(b) Toward the bottom of the page
(c) Into the page
(d) Out of the page
(e) The magnetic field is in the direction of the curved path.

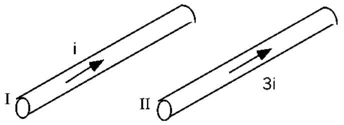


23. Wire 1 has a large current i flowing out of the page (⊙), as shown in the diagram. Wire 2 has a large current i flowing into the page (⊗). In what direction does the magnetic field point at position P?



(a) ↑ (b) ← (c) → (d) ↓ (e) none of the above.

24. Two parallel wires I and II that are near each other carry currents i and 3i both in the same direction. Compare the forces that the two wires exert on each other.



(a) Wire I exerts a stronger force on wire II than II exerts on I.
(b) Wire II exerts a stronger force on wire I than I exerts on II.
(c) The wires exert equal magnitude attractive forces on each other.
(d) The wires exert equal magnitude repulsive forces on each other.
(e) The wires exert no forces on each other.

25. The figures below represent positively charged particles moving in the same uniform magnetic field. The field is directed from left to right. All of the particles have the same charge and the same speed v. Rank these situations according to the magnitudes of the force exerted by the field on the moving charge, from greatest to least.

(a) I = II = III

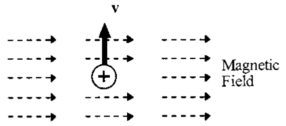
(b) III > I > II

(c) II > I > III

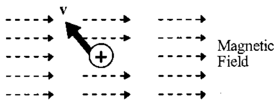
(d) I > II > III

(e) III > II > I

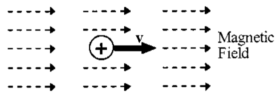
I



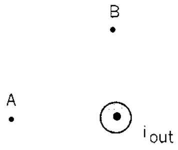
II



III

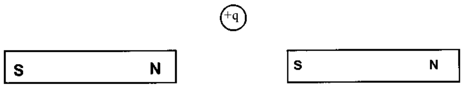


26. The diagram shows a wire with a large electric current i (⊙) coming out of the paper. In what direction would the magnetic field be at positions A and B?



	A	B
(a)	↓	←
(b)	→	↓
(c)	↑	→
(d)	←	↑
(e)	None of these	

27. A positively-charged particle (+q) is at rest in the plane between two fixed bar magnets, as shown. The magnet on the left is three times as strong as the magnet on the right. Which choice below best represents the resultant **MAGNETIC** force exerted by the magnets on the charge?



(a) → (b) ↙ (c) ← (d) ↘ (e) Zero

28. Two identical loops of wire carry identical currents i. The loops are located as shown in the diagram. Which arrow best represents the direction of the magnetic field at the point P midway between the loops?

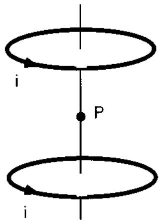
(a) ↓

(b) →

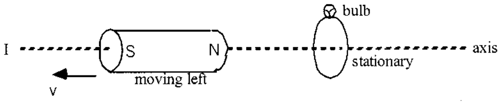
(c) ↑

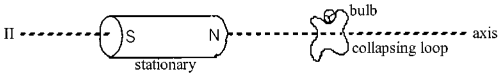
(d) ←

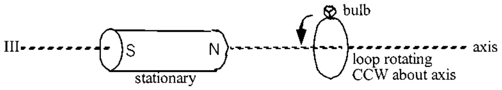
(e) Zero

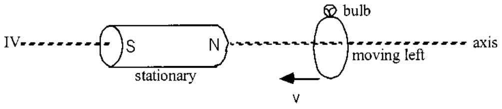


The five separate figures below involve a cylindrical magnet and a tiny light bulb connected to the ends of a loop of copper wire. These figures are to be used in the following question. The plane of the wire loop is perpendicular to the reference axis. The states of motion of the magnet and of the loop of wire are indicated in the diagram. Speed will be represented by v and CCW represents counter clockwise.







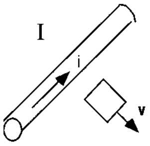


29. In which of the above figures will the light bulb be glowing?

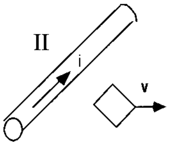
(a) I, III, IV (b) I, IV (c) I, II, IV (d) IV (e) None of these

30. A very long straight wire carries a large steady current i. Rectangular metal loops, in the same plane as the wire, move with velocity **v** in the directions shown. Which loop will have an induced current?

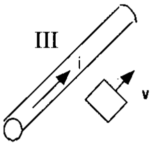
I



II



III



(a) only I and II

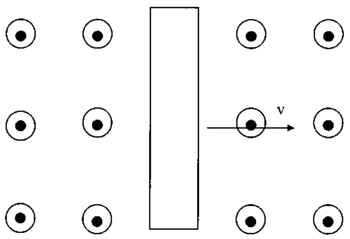
(b) only I and III

(c) only II and III

(d) all of the above.

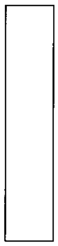
(e) none of the above.

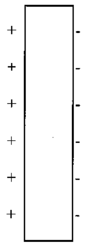
31. A neutral metal bar is moving at constant velocity v to the right through a region where there is a uniform magnetic field pointing out of the page. The magnetic field is produced by some large coils which are not shown on the diagram.

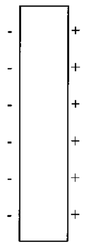


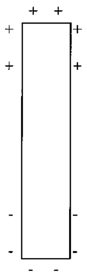
B out of page

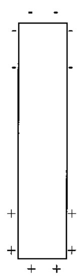
Which one of the following diagrams best describes the charge distribution on the surface of the metal bar?


(a)

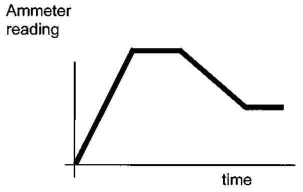

(b)

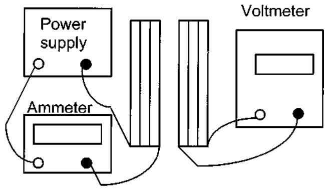

(c)


(d)

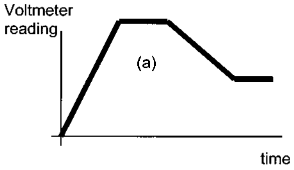

(e)

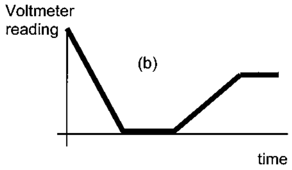
32. A variable power supply is connected to a coil and an ammeter, and the time dependence of the ammeter reading is shown. A nearby coil is connected to a voltmeter.

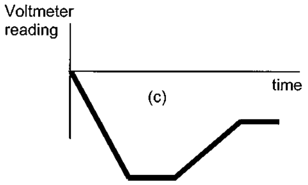


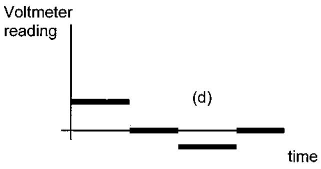


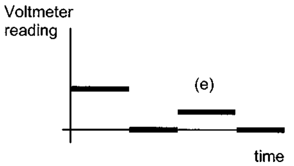
Which of the following graphs correctly shows the time dependence of the voltmeter reading?











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