Journal of Science Education and Technology (© 2007)
DOI: 10.1007/s10956-007-9051-9

How Much Have They Retained? Making Unseen Concepts Seen in a Freshman Electromagnetism Course at MIT

Yehudit Judy Dori,[1,2,4] Erin Hult,[3] Lori Breslow,[2] and John W. Belcher[2]

The introductory freshmen electromagnetism course at MIT has been taught since 2000 using a studio physics format entitled TEAL—Technology Enabled Active Learning. TEAL has created a collaborative, hands-on environment where students carry out desktop experiments, submit web-based assignments, and have access to a host of visualizations and simulations. These learning tools help them visualize unseen electromagnetic concepts and develop stronger intuition about related phenomena. A previous study has shown that students who took the course in the TEAL format (the experimental group) gained significantly better conceptual understanding than those who took it in the traditional lecture-recitation format (the control group). The present longitudinal study focuses on the extent to which these two research groups (experimental and control) retain conceptual understanding about a year to 18 months after finishing the course. It also examines students attitudes about whether the teaching format (TEAL or traditional) contributes to their learning in advanced courses. Our research has indicated that the long-term effect of the TEAL course on students' retention of concepts was significantly stronger than that of the traditional course. This research is significant because it documents the long-term cognitive and affective impact of the TEAL studio physics format on learning outcomes of MIT students.

KEY WORDS: conceptual understanding; electromagnetism; longitudinal study; retention; undergraduate physics education; visualization

INTRODUCTION

Studies of how much conceptual understanding college students retain from their science courses are quite rare. Related studies include Barufaldi and Spiegel (1994), and Martenson *et al*. (1985). As Halpern and Hakel (2003) have discussed, educators need to provide students with education that lasts a lifetime. Thus, instructors need to adopt teaching and learning strategies for long-term retention in order for their students to remember what they have learned beyond the end of the semester.

Beginning in 2000, the introductory freshmen electromagnetism course (E&M) at MIT has been taught using a new approach—Technology-Enabled Active Learning (TEAL). This study was reported by Dori and Belcher (2005a, b). The objective of the TEAL Project was to reform a mandatory large-enrollment physics class in order to increase students' conceptual understanding of electromagnetism and decrease failure rates in the course. The problems with passive learning in large classes were identified and researched over a decade ago (Hake, 1998; McDermott, 1991; Redish *et al*., 1997; Sokoloff and Thornton, 1997). The TEAL approach advocates an active learning method and the use of educational technology to help students better visualize, develop

[1]Department of Education in Technology and Science, Technion, Israel Institute of Technology, Haifa, 32000, Israel
[2]Massachusetts Institute of Technology, Cambridge, MA, 02139, USA
[3]Stanford University, Stanford, CA, 94305, USA
[4]Correspondence and reprint should be addressed:
E-mail: yjdori@technion.ac.il

stronger intuition about, and create more robust conceptual models of electromagnetic phenomena.

In the previous study (Dori and Belcher, 2005a, b) we used pre-and post-tests which were administered to students taking the class in the TEAL format and to those taking the class in the traditional lecture-recitation format. We showed that students who took the course in the TEAL format gained significantly better conceptual understanding than those who took it in the traditional format. This current longitudinal study focuses on the extent to which the two research groups retain conceptual understanding about a year to 18 months after finishing the course. As part of this study, we also investigated the perceptions of both groups about the effect of the pedagogical methods used in the electromagnetism course on their learning in advanced courses.

A number of researchers have investigated the relationship between high school students' retention of course materials and their achievements in higher education. These studies have shown that an inquiry-based laboratory in biology is positively related to success in undergraduate studies (Novak *et al*., 1971; Tamir and Amir, 1981). In addition, some researchers have indicated that retention and long-term outcomes of meaningful school materials can persist from one course to another, even over relatively extended intervals (Arzi *et al*., 1986). Other researchers have examined the relationship between the ability to retain certain learning skills and the time passed since acquiring these skills and their studies have shown similar results (Leonard, 1987; Leonard and Lowery, 1984; Otto and Schuck, 1983).

THE LEARNING ENVIRONMENT: VISUALIZING ELECTRICITY AND MAGNETISM IN A COLLABORATIVE CONTEXT

The TEAL project was designed to create a collaborative, hands-on environment where students can carry out desktop experiments, submit web-based assignments, and have access to a host of visualizations and simulations of electromagnetic phenomena. Elaborating on ideas from the Studio Physics project of Rochester Polytechnic Institute—RPI (Cummings *et al*., 1999) and the Scale-Up project of North Carolina State University—NCSU (Handelsman *et al*., 2004; Beichner *et al*., 2006), TEAL extended these efforts by incorporating advanced 2D and 3D visualizations that employ such techniques as movies and Java applets. These visualizations support meaningful learning by enabling the presentation of spatial and dynamic images that portray relationships among complex concepts. They also allow students to gain insight into the way in which fields transmit forces by watching how the motion of objects evolve in time in response to those forces.

The TEAL format uses visualizations to teach physics interactively in freshman courses at MIT (classes of 500–600 students divided into groups of 120). It combines desktop experiments with visualizations of those experiments to ''make the unseen seen.'' The pedagogy utilizes the following elements:

- Collaborative learning: nine students sit at a round table and discuss electromagnetism phenomena, and students work in groups of three to perform desktop experiments and analyze the data from their experiments.
- Networked laptops, one for each group of three, with data acquisition links to desktop experiments.
- Instructors move among the tables and discuss experiment outcomes with the students (see Figure 1).
- Media-rich software for multimedia visualization is delivered via class laptops and the Web (see Figures 2–10).
- Extensive course notes have links to the visualizations.
- A personal response system (PRS) enables students to respond electronically to real-time questions posed by the professor.
- Embedded assessment includes both individual and team grades for pre-class assignments via the web, laboratory reports, end-of-week problems, and class participation in the PRS conceptual questions.

The visualizations developed especially for this course are organized in five categories: Vector Fields, Electrostatics (see Figures 2–4), Magnetostatics (see Figures 5–7), Faraday's Law (see Figures 8–9), and Light (see Figure 10). This paper presents a selection from over 100 visualizations accessible at http://web.mit.edu/8.02t/www/802TEAL3D/teal_tour.htm.

These visualizations range in format from passive mpeg movies to interactive Shockwave and Java 3D applets.

An animation of the electric fields around a van de Graaff generator as it repels a positive charge is presented in Figure 2. It shows both the ''moving field lines'' and the ''dynamic line integral convolution'' representation of the electric field. Correlations in the animated texture indicate the direction of the field.

Figure 3 presents an Ion Trap. It includes twelve identical charges in a potential well, which forces them together against their mutual repulsion.

Figure 4 shows an ''electrostatic suspension bridge,'' illustrating how matter is held together against gravity by electrostatic bonds. These bonds can be broken under sufficient stress. Pressing a key repeatedly adds a ''rain'' of neutral particles until the bridge collapses under its weight.

Fig. 1. A TEAL classroom scene: students and instructors discuss experiment outcomes.

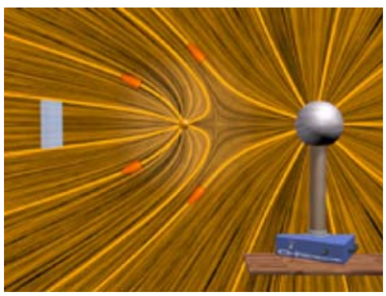


Fig. 2. Electrostatics—a Van de Graff generator repelling a charge.

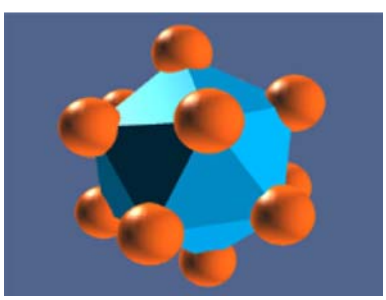


Fig. 3. Electrostatics—the ion trap.

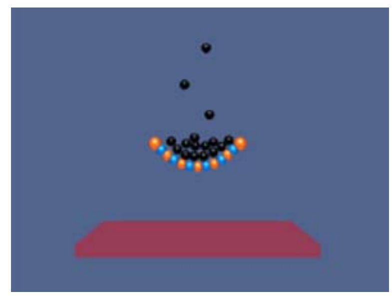


Fig. 4. Electrostatics—the suspension bridge 2D.

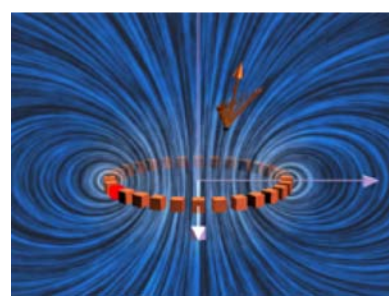


Fig. 5. Magnetostatics—integrating around a ring of current.

Figure 5 visualizes the use of the Biot-Savart Law and illustrates how to calculate the magnetic field of a ring of current made up of many individual current elements. Various controls enable dragging to change the view and the point at which the magnetic field is calculated, and highlight the contribution of a given current element to the magnetic field.

Figure 6 shows an animation of the magnetic field and the forces that are generated by two parallel wires when the currents in the wires run in opposite directions. When the current is turned on, the resulting pressure of the magnetic field between the wires pushes them apart.

The animation in Figure 7 presents a magnetic field generated by two coils carrying unequal currents in opposite directions. When the current is turned on, the resulting pressure of the magnetic field between the two rings pushes them apart. The motions of the field lines are in the direction of the local Poynting flux vector, and show the electromagnetic energy flow from the wires (where it is created) to the space between the wires.

The magnetic field configuration in Figure 8 is generated around a conducting non-magnetic ring (e.g., copper) as it falls under gravity in the magnetic field of a fixed permanent magnet. The current in the

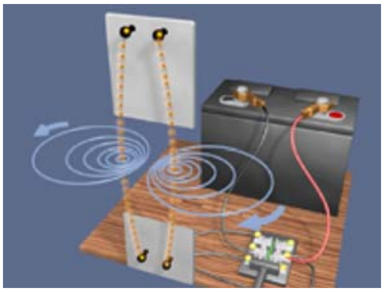


Fig. 6. Magnetostatics—two wires in series.

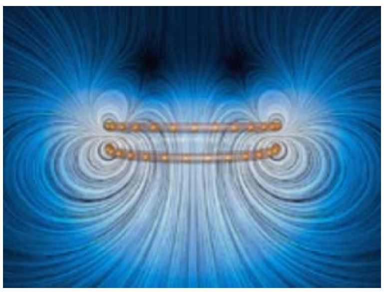


Fig. 7. Magnetostatics—two rings of current repelling.

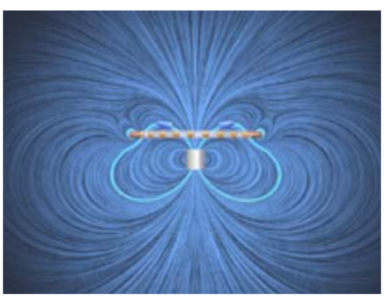


Fig. 8. Faraday's law—the falling ring with finite resistance.

ring is indicated by the small moving spheres. In this case, the ring has finite resistance and it falls past the magnet.

The interactive Java 3D applet in Figure 9 shows the field configuration around a non-magnetic ring as it falls under gravity in the field of a fixed magnet. In the initial configuration, the coil is light and has zero resistance and thus levitates in the field of the magnet, bouncing up and down. The viewer can use a slider to increase the resistance, and the ring will then fall past the magnet due to ohmic resistance. At any point the viewer can hit a button to see a representation of the complete field.

An animation of electric dipole radiation is presented in Figure 10. The dipole moment vector is

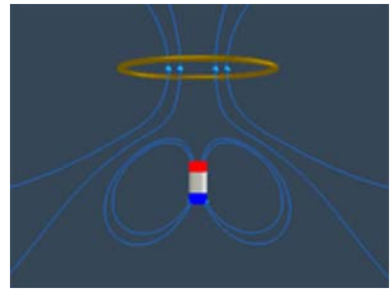


Fig. 9. Faraday's law—the falling coil applet.

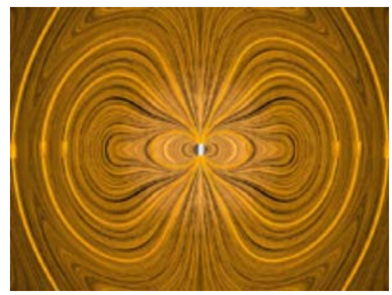


Fig. 10. Light—electric dipole radiation.

always vertical, and its magnitude varies sinusoidally with amplitude of 10%. The visualization shows the fields in the quasi-static zone, the induction zone, and the radiation zone. The motions of the field lines are in the direction of the local Poynting flux vector.

METHODOLOGY

Research Questions

The two research questions were:

1. What is the long-term impact of the TEAL project on the retention of students' conceptual understanding of electromagnetism, and how does this long-term impact of TEAL compare to the impact of the traditional teaching method?
2. How do students perceive the contribution of studying E&M in one format or the other to their learning in advanced courses?

Research Settings, Methods, Instruments, and Population

The TEAL experiment originally started with a pilot study that was conducted in Fall 2000 and continued throughout Fall 2001 with about 100 students each semester (Dori *et al.*, 2003). It evolved into a large-scale implementation that included approximately 600 students who enrolled in the E&M class in Spring 2003. The initial assessment examined students' conceptual understanding of electromagnetic phenomena before and after the course, and the effect of this learning environment on students' preferences regarding the various teaching methods. Both quantitative and qualitative research methods were used. The research tools included pre-tests, post-tests, surveys, and focus groups.

The current longitudinal assessment effort used similar methods and tools.

Each test (pre-, post-, and retention) consisted of 25 multiple-choice conceptual questions[5] from standardized tests (Maloney *et al.*, 2001; Mazur, 1997; McDermott and the Physics Education Group, 1996) augmented by questions that the instructors and researchers devised. There were two types of conceptual questions, A and B (see Appendices I and II). Both types contained similar questions with slight variations to avoid the effect of prior exposure in the pre-test to questions that would later appear in the post-test. In the original study about half of the students responded to the type A pre-test and the type B post-test. The other half responded to the type B pre-test and the type A post-test. For the retention test in the current study, we again randomly mixed the two test types, so each student responded to type A or type B test.

In order to address the first research question—the long-term impact of the TEAL project on the students' retention—the same test from the original research (i.e., a mix of both types) was administered to the experimental and control groups in the longitudinal (retention) research. This retention test was taken by volunteer students from both research groups approximately a year to 18 months after having taken the course. At that stage, the students were already at their third or forth year of undergraduate studies. Their specializations spanned a wide variety of engineering and science disciplines. Among the volunteers, 120 had taken E&M physics in the TEAL format, while 52 had taken it in the traditional format. The difference in group sizes stems from the fact that about 600 TEAL students and only about 120 from the control (the traditional course) students participated in the original study.

Mean scores, standard deviations, and *t*-tests were calculated for the pre-, post-, and retention tests of each research group. Statistical analysis of the results revealed no significant differences between the two test types.

For the second research question, the students responded to the following two open-ended questions:

1. *Please elaborate on the contribution of studying E&M in the TEAL format or in the traditional format to your learning in advanced courses.*
2. *How and to what extent did the visualizations contribute to your comprehension of E&M concepts?*

Each response from the students' comments underwent content analysis and was classified into one or more categories.

FINDINGS

Quantitative

Table I presents results of the comparison between experimental and control upper class students on the three test types. There was no significant difference between the two research groups in the pre-test. However, in both the post-test and the retention test, TEAL students significantly outperformed their control peers. The average E&M course net gain (Post–Pre score) of the experimental students was 36 (out of 100) compared with a net gain of 16 for the control students. The average retention net gain (Retention—Pre score) of the experimental students was 23 compared with a net gain of 15 for the control students.

As Table I shows, the TEAL approach yielded significantly better learning outcomes than the traditional approach. This significant difference persisted even 18 months after the end of the course. The gain of the experimental group at the end of the course was twice as much as that of the control group. Therefore, the potential for failing to remember the E&M content matter was higher. Nonetheless, the retention of the experimental students remained significantly higher than that of their peers.

Qualitative

Figures 11 and 12 show the reactions of students who were enrolled in the TEAL (experimental) and traditional (control) courses in response to the second

[5]Questions 10, 16, 23, 24, and 25 in both conceptual test types (A & B) were not used for the analysis of TEAL experimental vs. control group studies of Dori Y. J. and Belcher, J.W. "How Does Technology-Enabled Active Learning Affect Undergraduate Students' Understanding of Electromagnetism Concepts?," The Journal of the Learning Sciences, 14(2), 243-279, (2005a).

Table I. Mean Scores, Standard Deviation, and *t*-test of Pre-, Post- and Retention Tests by Research Group

Test type	Research group	*N*	Mean score	SD	*t*-Value	*p*
Pre	Experimental	120	33	13	0.68	n.s.
	Control	52	32	9		
Post	Experimental	120	69	16	8.03	< 0.0001
	Control	52	48	16		
Retention	Experimental	120	56	15	3.37	< 0.005
	Control	52	47	15		

n.s., non-significant.

research question: "*How do students perceive the contribution of studying E&M in one format or the other to their learning in advanced courses*?" Figure 11 illustrates the percentages of students in the experimental and control groups making all positive, all negative, mixed comments (both negative and positive), or neutral comments in response to the open-ended "*Please elaborate on the contribution of studying E&M in the TEAL format or in the traditional format to your learning in advanced courses*." The percentage shown is the number of students in a research group making, for example, all positive comments, divided by the number of total students in that group. The neutral category consists almost entirely of students commenting exclusively that they had no further courses that required the material from the introductory E&M course.

Figure 11 shows that the experimental students had stronger feelings (both positive and negative) than control students. The control students were "more comfortable" with a strategy they were familiar with, an approach that advocates passive learning and studying only to the tests.

Table II presents examples of items that students from the experimental and control groups made in response to the open-ended question regarding the teaching approach in the E&M course they took.

Figure 12 shows the perceived benefits of studying physics in the TEAL or traditional formats. The percentages shown are equal to the number of students within the experimental or the control group making a comment in a particular category divided by the number of students in the corresponding group. In general, the two groups made similar numbers of positive comments per student, with 1.03 positive comments per student in the TEAL group verses 1.04 in the traditional group.

The largest discrepancies between the two groups appear in the categories of enjoyment and confidence, group and instructor interaction, interest and motivation, lecture and explanations, visualization and experiments, and multiple methods and conceptual understanding. On the one hand, the strengths of the experimental approach over the traditional approach highlight the additional elements in the experimental course: group work, visual and hands-on activities, and the incorporation of multiple methods in building conceptual understanding. On the other hand, the control group made positive comments more frequently regarding enjoyment, interest, and quality of lectures.

The difference in the types of comments made by the two groups suggests that students may be resistant to departures from traditional methods. For example, one control group student commented, "*I*

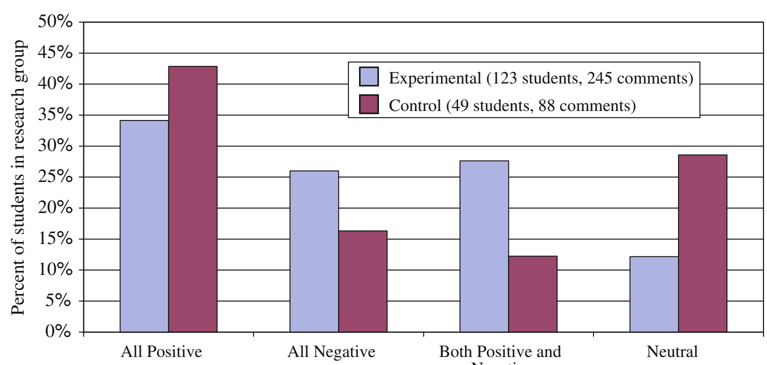


Fig. 11. Comparison of positive and negative items expressed by the two research groups.

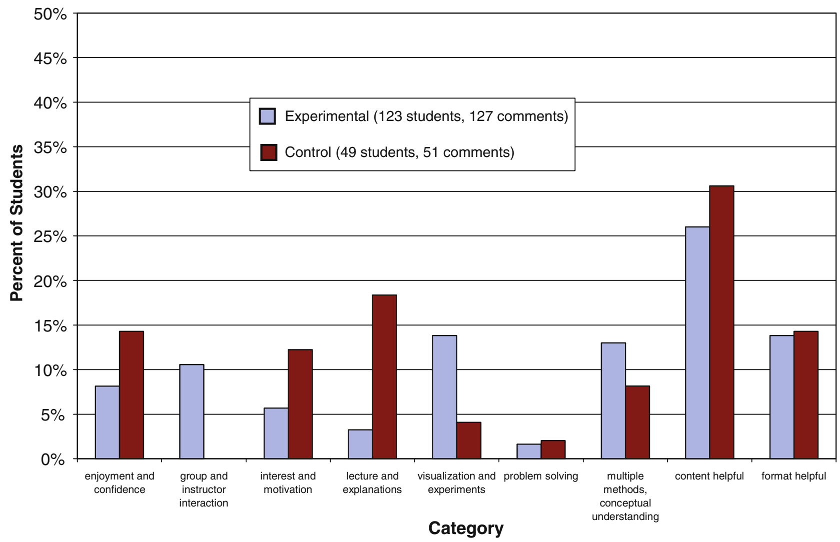


Fig. 12. Comparison of students' positive attitudes toward studying E&M in the TEAL vs. the traditional format.

liked taking E&M in big lecture format. This seems like a traditional part of an MIT education.'' Despite the fact that the smaller lecture size appealed to some experimental students, others in the experimental group expressed interest in the traditional format. For example one TEAL student commented: ''*I would have preferred the regular lecture method of studying, for I felt that I got very little out of doing the in-class labs, so it would have been more beneficial to have seen the lab done by a professor and spent the time we wasted on going over material and examples.*'' However, a substantial percentage of experimental students commented that group or instructor interaction, one of the new elements of the course, had made a positive contribution to the experience.

In regard to preparation for advanced courses, 11% of the experimental students vs. only 4% of the control group students praised group or instructor

Table II. Items Cited by Students from the Two Research Groups Regarding the Teaching Approach

	Experimental group	Control group
Positive	''Learning in TEAL format was helpful in seeing the big picture concepts. We spent more time going over the basic ideas than just going through complicated math problems. This was aided by PRS and also by my instructor doing a good job to make sure people understood the concepts amidst the many resources that often created confusion. This taught me to step back and try to grasp qualitative concepts first before trying to get quantitative ones.''	''I liked taking E&M in big lecture format. This seems like a traditional part of an MIT education. [The lecturer] was very clear in his description.''
Mixed	''I think the only thing I got out of TEAL was a reinforcement of what I learned in high school. This reinforcement came from the fact that I basically taught my table the material. I liked our professor and he would have been an awesome lecturer had he not had to work with PowerPoint. Deriving Maxwell's equations slide by slide will never be the same as doing them by hand.''	''The traditional format of learning is very similar to my advanced classes.... I feel that the E&M traditional format gave me a good, but not in-depth background of E&M.''
Negative	''I did not find the TEAL format particularly effective for me in learning the material. Concepts taught in class time did not stick with and most of my learning came from cramming for tests and the problem sets. I really don't feel I benefited by going to class and would have been better off reading the book instead.''	''I feel that I would have learned more from a more intimate environment with individual attention. It was easy to skip classes and not care in a large lecture. Because I am not strong in Physics, I could have used a lot more guidance.''

Table III. Items Cited by Students from the Two Research Groups Regarding Visualizations

	Experimental group	Control group
Positive	"I thought the 2D and 3D applets were helpful. I think with E&M it is much easier to learn visually because there are so many directions and things change drastically if you manipulated distances, charges, etc. So just getting an equation or hearing about wouldn't help as much as seeing it and being able to manipulate it yourself."	"Some of the crazy stuff [the lecturer] did helped me remember material simply because he was ridiculously funny. One time he put himself in a metacage and charged up the outside while he stood inside, banging on the cage and singing. That's how I figured out Question 2 on this [retention] test."
Mixed	"I found them only minimally helpful, reading/doing problems/ hearing lecture is needed to really get full understanding, seeing a visualization lets you visualize what is going on but this does not mean you will understand it. Visualizations don't seem to be a necessary contributing factor in allowing me to understand the material."	"Very helpful, but they were used sparingly in traditional E&M. I feel the course would benefit from increased use of the web, especially for 3D visualization." "Nice but not necessary."
Negative	"Not very effective; it is a change of pace and if incorporated correctly, visualizations could be very beneficial, but too often I didn't have the understanding to comprehend the visuals."	"I didn't do much of that at all when I took E&M."

interaction. For example, a TEAL students commented, "TEAL was good in a sense that we shared a group learning experience. This has continued to help me work in groups. TEAL made the material easier to understand. It felt like a smaller class rather than a huge lecture."

The topic of visualizations and experiments was mentioned as a contributing factor by 14% of experimental students vs. 8% of the control students. Table III presents examples of students' comments regarding the use of visualizations in their E&M course. As Table III shows, the experimental students related to the virtual visualization, while the control group students—to the professor's demonstrations. Multiple methods and conceptual understanding, which were primary goals of the TEAL project, were cited by 11% of the experimental students as opposed to none of the control group. One experimental student commented, "*TEAL demanded active classroom participation which would have been absent in the traditional setting. I enjoyed each session*'s multiple choice problems that asked for every student's input with the remote control. This forced me to quickly absorb what was said in lecture and review material on a small scale. The hands on experiments also helped to visualize the concepts and theories and made formulae less tedious."

In the control group, many students commented on the ability of the lecturer, who was renowned as an excellent teacher, to make the course interesting and enjoyable. One control student wrote, "*The professor was an engaging instructor who made learning theory an experience of its own*."

It should be noted that most of the TEAL instructors did not participate in the development of learning materials for TEAL and were new to the TEAL format.

Figure 13, which presents students' negative comments, shows that almost half of the traditional class students who responded to the attitude questionnaire noted that they did not study advanced courses that built on the E&M material (unlike the TEAL students).

Figure 14 presents the percentages of experimental and control students making positive comments in various categories when asked to comment on the question about visualizations: "*How and to what extent did the visualizations contribute to your comprehension of E&M concepts?*" Experimental students were more likely to comment that visualizations helped gaining conceptual understanding and were helpful in particular areas such as field theory, wave mechanics, and abstract topics. Control students, on the other hand, were much more likely to express their enjoyment of the visualizations, primarily demonstrations, used in the course. Control students were also more likely to comment that visualizations helped memory retention of concepts.

Table IV summarizes students' comments regarding the use of E&M knowledge or skills in advanced courses. As Table IV shows, some TEAL students used the material studied in E&M in advanced courses where they applied concepts and intuition gained in the course. Both research groups included students who did not use the material taught

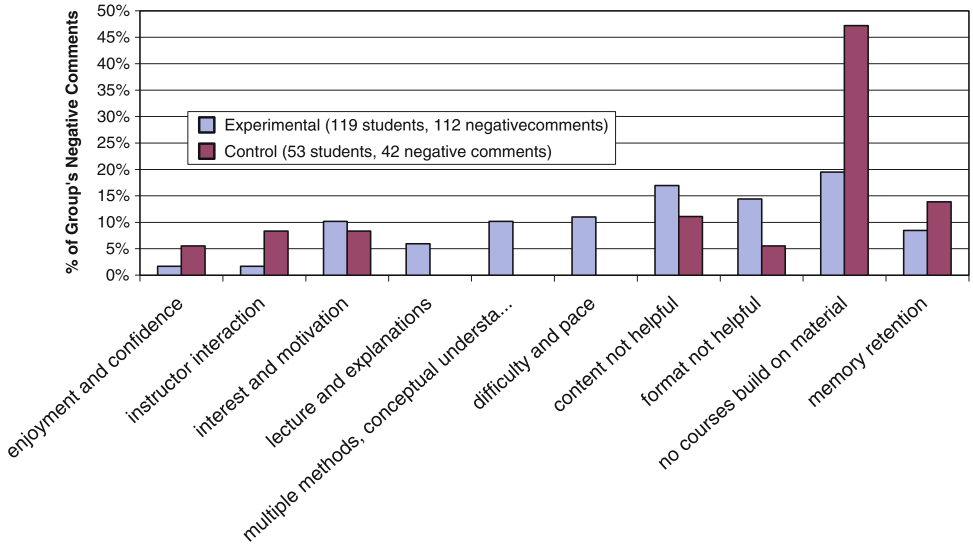


Fig. 13. Comparison of negative items expressed by the two research groups.

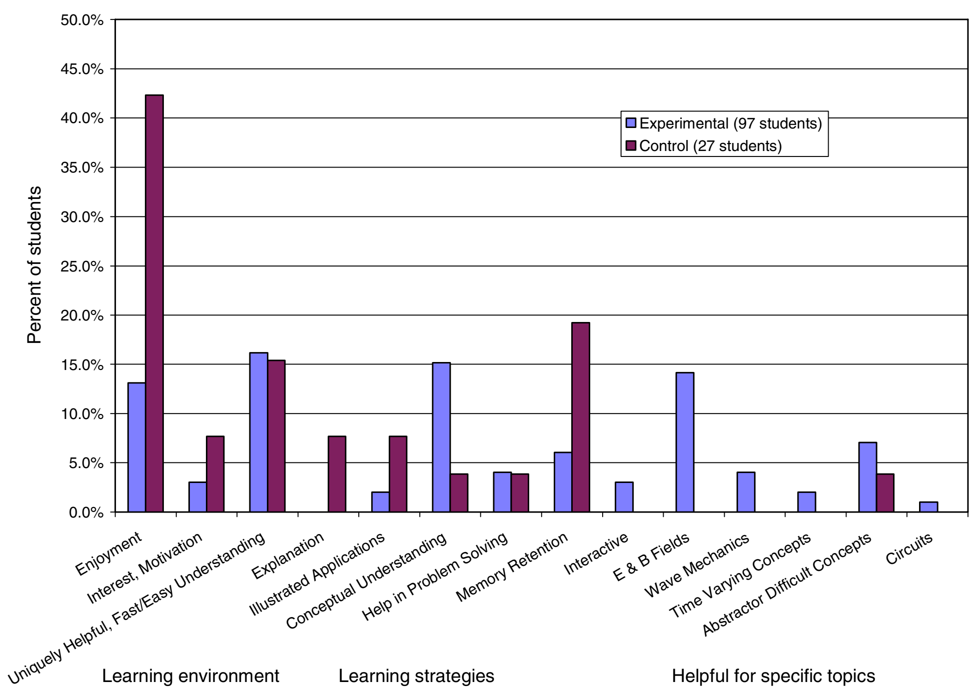


Fig. 14. Distribution of positive comments on visualization by the two research groups.

in the E&M course and therefore, had mixed feelings regarding the value of this mandatory course to their advanced studies.

SUMMARY AND DISCUSSION

Animation is a dynamic depiction that can be used to make change processes explicit to the learner (Schnotz and Lowe, 2003). However, creating learning environments that contain visual effects is not sufficient for promoting cognitive processing and improving learning. The instructor has to correctly plan the manner in which the information is presented and adapt it to the students' cognitive abilities and styles (Frank, 2006; Frank and Elata, 2005). Lowe (2003) and Lewalter (2003) indicated that

Table IV. Items Cited by Students from the Two Research Groups Regarding the Use of E&M Knowledge or Skills in Advanced Courses

	Experimental group	Control group
Positive	"Some of the stuff we learned in E&M TEAL involving charges and fields has been useful in our quantum classes. Our electrical, optical, and magnetic properties of materials class/lab use capacitors, resistors, and other circuitry that is similar to what we studied in E&M a year ago."	"Although I don't use the material from E&M in my advanced courses, I think that the class helped me to learn how to study difficult material and to think about the application of theoretical principles to real design problems."
Mixed	"I haven't used E&M that much except for some circuits. I am Course 3 [Material Science and Engineering]. I felt the challenge to my intuition that E&M provided was a valuable learning experience though."	"Very little of what I learned was applicable. In my laboratory classes, knowledge of circuitry was useful, but I feel I would have benefited from a more hands-on or experimental approach. E&M was also useful for general knowledge of E&B fields, but what we needed to remember was explicitly covered in advanced courses."
Negative	"I feel like the over-emphasis of concepts and visualizations left me somewhat unprepared for more practical advanced courses."	"I think that the way I learned E&M was more quantitative so it doesn't really apply to the more qualitative learning in biology courses."

merely providing learners with the dynamic information in an explicit form does not necessarily result in better learning.

As Mayer (2002) noted, two of the most important educational goals are to promote retention and transfer. The present study has shown that the TEAL approach with its visualizations, hands-on activities, focus on conceptual understanding, and embedded assessment (both individual and in teams) yielded significantly better learning outcomes than the traditional lecture/recitation approach. This significant difference persisted even a year to 18 months after the end of the course. Since the gain of the experimental group was double that of the control group, the potential for "forgetting" was higher, but, nonetheless, the retention of the experimental students remained significantly higher than their peers. This is in accordance with another study of high school honors students' retention that investigated a computerized chemistry laboratory environment which emphasized visualizations, teamwork, hands-on activities, and embedded assessment (Dori and Sasson, 2008). The present research also indicated that some TEAL students were able to transfer the knowledge and skills from the TEAL E&M course to advanced courses.

These findings reinforce the notion by Halpern and Hakel (2003) who claim that learning occurs under varied conditions, and key ideas have "multiple retrieval cues" that allow them to be retrieved. They go on to say that some learning situations and methods require a greater investment of effort both on the part of students and instructors than others. Consequently, some learning situations may be less enjoyable for students, leading to lower instructors' ratings. This is, indeed, part of what may have happened in this study: While TEAL students' learning gains were significantly higher than their peers', they responded with a higher number of negative comments. Students' resistance to changes introduced by the TEAL project was a major source of dissatisfaction. For example, a TEAL student wrote: "*I think there are too many variables to hold a firm position either way. A lot depends on the instructor and on the format of the course that semester. It also depends a lot on how a particular student prefers to learn—obviously we are all accustomed to lecture format, and some people like that while others might like TEAL.*" Comments such as this suggest that the personality and experience of the lecturer play a major role in the attitudes of students toward any course. The experimental group was taught by six different lecturers who did not participate in the development process of the new learning materials, while the traditional class was taught by a highly experienced professor who designed his own class materials. One key area that could improve student attitudes toward visualization techniques and the experimental course in general is providing clear, interesting, and enjoyable explanations, although obviously this is no trivial task.

Currently, the TEAL format is also being introduced to the mechanics course that precedes the E&M course, so freshmen have an opportunity to become accustomed to the new approach and, thus, may possibly be less resistant because this teaching and learning format will no longer be perceived as a major change.

In summary, this research has shown that statistically significant differences exist between the TEAL format and the traditional format in regard to students' retention of E&M concepts. In addition, in response to the open-ended questions, experimental students noted that teamwork, visualizations, hands-on activities, and the incorporation of multiple methods were positive factors that enhanced their conceptual understanding and retention of material. However, this research has also indicated that students may have quite a bit of resistance to pedagogical strategies that differ sharply from traditional teaching and learning strategies that they became accustomed to during their high school education. The importance of this research is that it documents longitudinal impact of the TEAL approach on the learning outcomes of MIT students in both the cognitive and the affective domains.

ACKNOWLEDGEMENTS

The TEAL project is supported by the d'Arbeloff Fund, the MIT/Microsoft iCampus Alliance, NSF Grant #9950380 and the MIT School of Science and Department of Physics.

Thanks to the director of Center for Educational Computing Initiatives (CECI), Steve Lerman for hosting the first author during the research period.

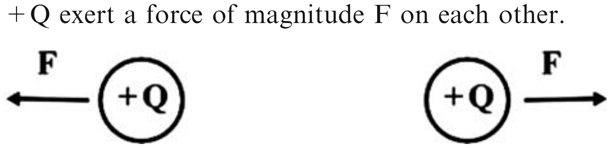
Thanks to the CECI staff: Andrew McKinney, Philip Bailey, Michael Danziger, Mesrob Ohannesian, Pierre Poignant, Ying Cao (*Java Simulations*); Mark Bessette, Michael Danziger (*3D Illustration/Animation*); Michael Danziger (*Shockwave Visualizations*); Andreas Sundquist (DLIC), Mesrob Ohannessian (IDRAW) (*Visualization Techniques R&D*).

APPENDIX I

ELECTROMAGNETISM A
MIT DEPARTMENT OF PHYSICS

Instructions: Please circle the letter corresponding to the correct choice in your pink score sheet.

(1) 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:

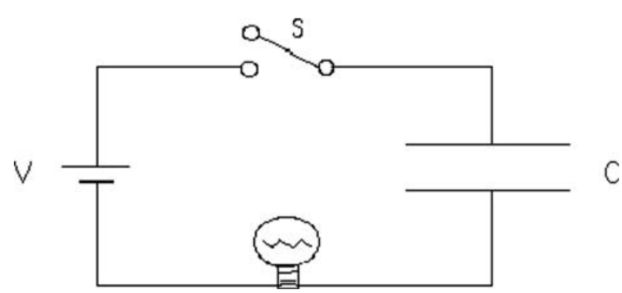
What is the magnitude of the force on the +4Q charge?

(a) 16F
(b) 4F
(c) F
(d) F/4
(e) None of the above.

(2) 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 is evenly distributed over the inside and outside surface.
(c) The excess charge has distributed itself evenly over the outside surface of the sphere.
(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.

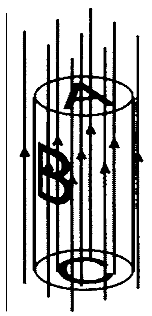
(3) The circuit below contains a battery, a capacitor, a bulb and a switch. The switch is initially open as shown in the diagram, and the capacitor is uncharged.



Which correctly describes what happens to the bulb when the switch is closed?

(a) The bulb is dim and remains dim.
(b) At first the bulb is dim and it gets brighter and brighter until its brightness levels off.
(c) The bulb is bright and remains bright.
(d) At first the bulb is bright and it gets dimmer and dimmer until it goes off.
(e) None of these is correct.

(4) The area vectors **dS** at each point on a closed surface (i.e., a surface that surrounds a volume) are always chosen to point *out of the enclosed volume*. A closed imaginary surface is called a Gaussian surface. The Gaussian surface below is a cylinder and is in a uniform electric field of magnitude *Eo* that is aligned with the cylinder axis.



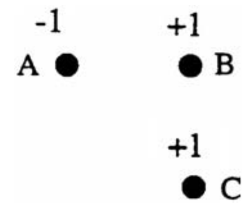
Which statement is correct about the flux $\int \mathbf{E} \cdot \mathbf{dS}$ through surface A and through the entire closed surface A + B + C?

(a) The flux through surface A is positive and through the entire closed surface it is positive.
(b) The flux through A is positive and through the entire surface it is negative.
(c) The flux through A is positive and the through the entire surface it is zero.
(d) The flux through A is negative and through the entire surface it is zero.
(e) The flux through A is negative and through the entire surface it is negative.

(5) 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). What happens to the electric potential energy (in joules) of the positive charge, after the charge is released from rest in the uniform electric field?

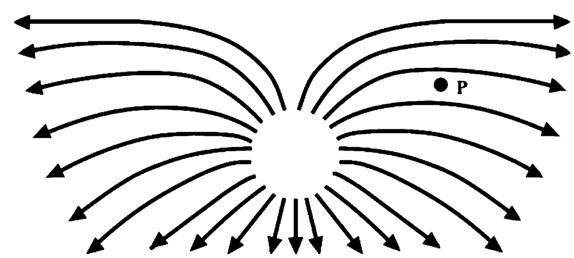
(a) It will remain constant because the electric field is uniform.
(b) It will remain constant because the charge remains at rest.
(c) It will increase because the charge will move in the direction of the electric field.
(d) It will decrease because the charge will move in the opposite direction of the electric field.
(e) It will decrease because the charge will move in the direction of the electric field.

(6) Three similar charged particles are placed one centimeter apart with the number of units of charge and the sign (+, −) of the charge indicated. Each charge is subject to electric forces caused by other charged particles.



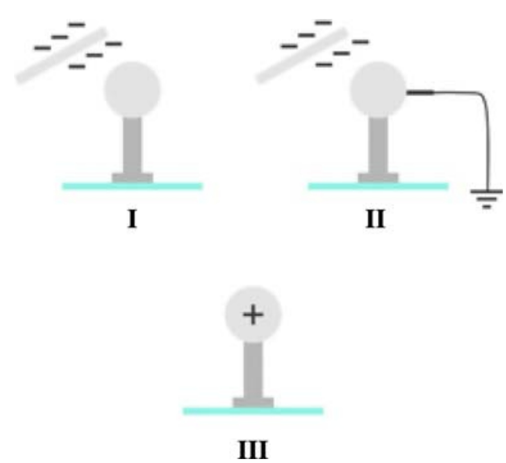
Which of the arrows is in the direction of the net force on charge B?

(7) Below is shown an electric field diagram.



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

(8) A negatively charged object is placed close to a conducting object attached to an insulating glass pedestal (I). After the opposite side of the conductor is grounded for a short time interval (II), the conductor becomes positively charged (III).



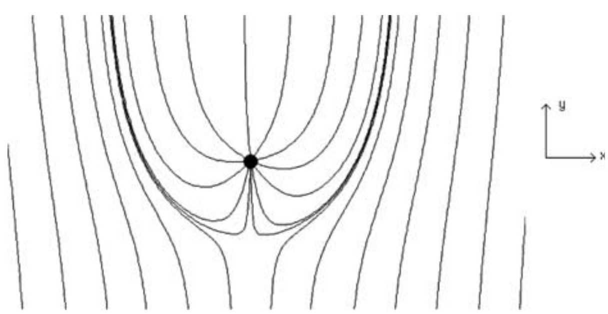
Based on this information, we can conclude that within the conductor:

(a) Both positive and negative charges move freely.
(b) Only negative charges move freely.
(c) Only positive charges move freely.
(d) Neither positive nor negative charges move freely.
(e) More information is needed.

(9) The A charged capacitor is connected to a battery. The battery remains connected while the region between the plates is filled with a dielectric.

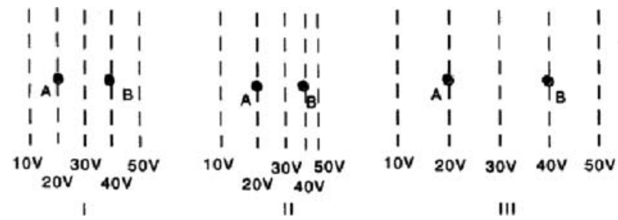
(a) The potential difference between the plates of the capacitor and its capacitance remain constant.
(b) The potential difference and the capacitance increase.
(c) The potential difference remains constant and the capacitance increases.
(d) The potential difference remains constant and the capacitance decreases.
(e) The potential difference decreases and the capacitance remains constant.

(10) The figure below shows the electric field lines (without arrows to indicate direction) for a constant electric field in the +y or −y direction plus those of a point charge. Choose the description below that describes the force on the point charge.



(a) The force is to the left.
(b) The force is upwards.
(c) The force is to the right.
(d) The force is downward.
(e) More information is needed.

(11) In the figures below, the dashed 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 $+1\ \mu C$.
How does the amount of work needed to move this charge compare for these three cases?

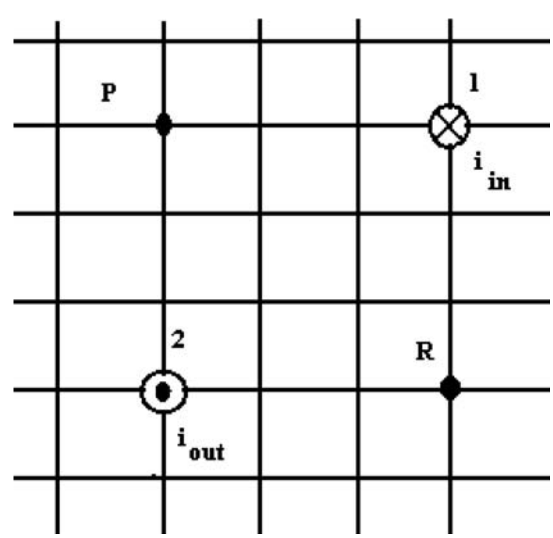


a. Most work required in I.
b. Most work required in II.
c. Most work required in III.
d. I and II require the same amount of work but less than III.
e. All three would require the same amount of work.

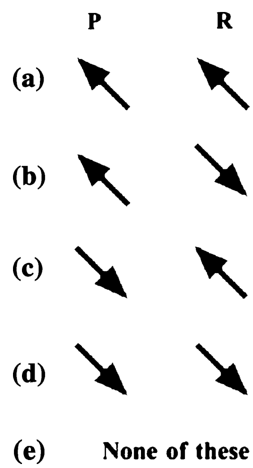
(12) An experiment shows that a magnetic force is acting on a particle. Which of the following is/are necessary for this magnetic force to exist?

a. The particle must be moving.
b. A magnetic field must be present.
c. The particle must be charged.
d. All of the above are required.
e. Both (b) and (c), but not (a).

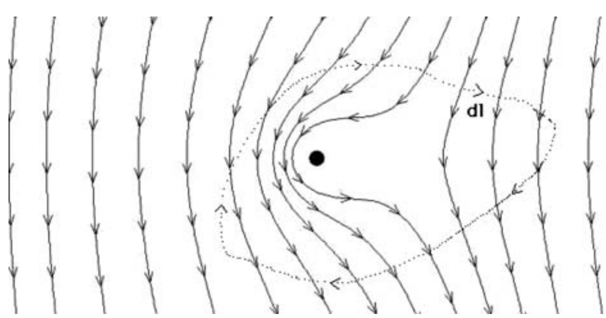
(13) Wire 1 has a large current i flowing into the page ⊗, as shown in the diagram. Wire 2 has a large current i flowing out of the page ⊙.



Which direction are the magnetic fields at positions P and R?



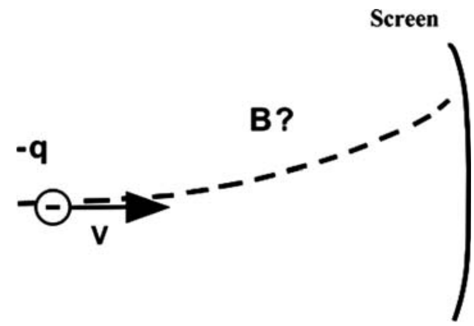
(14) The figure below shows the magnetic field lines of a current-carrying wire carrying a constant current, sitting in a constant magnetic field. The currents that generate the constant field are very distant and are not shown. The dotted line represents a closed contour with the sense of **dl** as shown.



When we evaluate $\oint \mathbf{B} \cdot \mathbf{dl}$ around this closed contour, the result we find is:

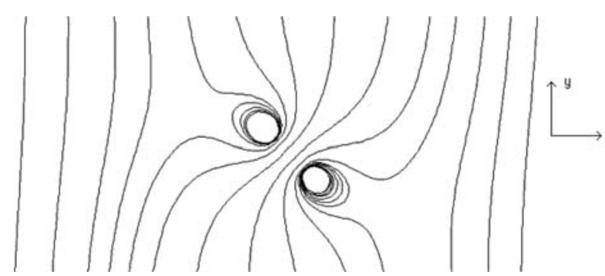
a. Non-zero and positive.
b. Non-zero and negative.
c. Zero.
d. More information is needed.
e. Indeterminate.

(15) 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?



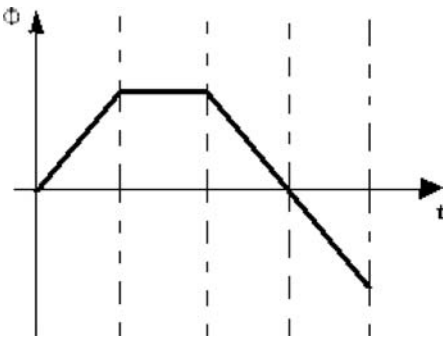
a. Toward the top of the page
b. Toward the bottom of the page
c. Out of the page
d. Into the page
e. The magnetic field is in the direction of the curved path.

(16) The figure below shows the magnetic field lines (without arrows to indicate direction) for a loop of current carrying-wire in a constant magnetic field in the $+y$- or $-y$-direction. The axis of the loop of current makes an angle of 45 degrees to the y direction. Choose the description below that describes the torque on the loop of wire.

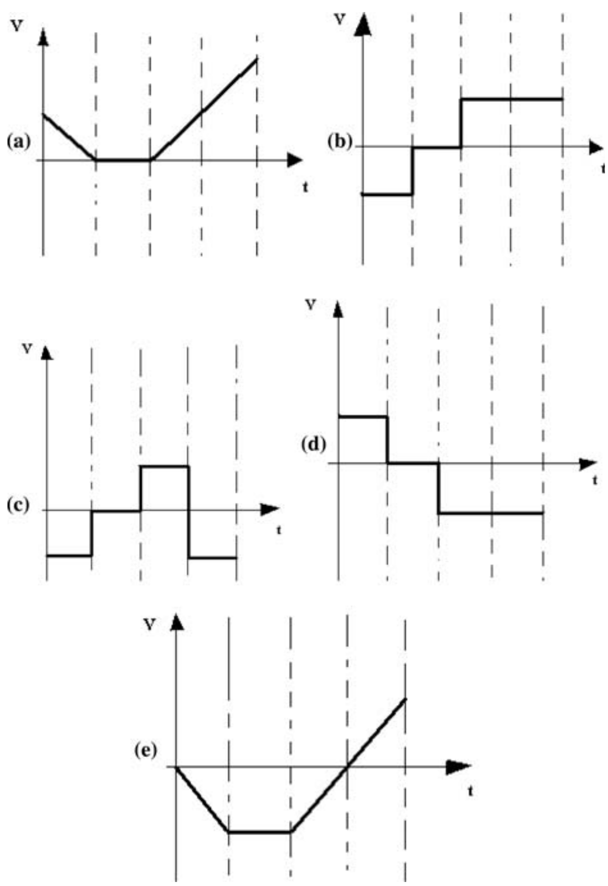


a. The torque is such that the coil of wire will rotate counterclockwise.
b. The torque is such that the coil of wire will rotate clockwise.
c. The torque on the coil of wire is zero.
d. More information is needed.
e. None of these is correct.

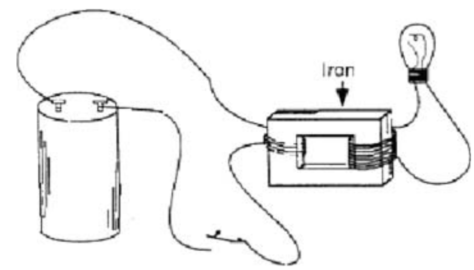
(17) A graph of the magnetic flux Φ through a coil as a function of time t is shown below:



Which graph below best represents the induced voltage V across the output of the coil? Induced voltage is the negative of the rate of change of the magnetic flux.

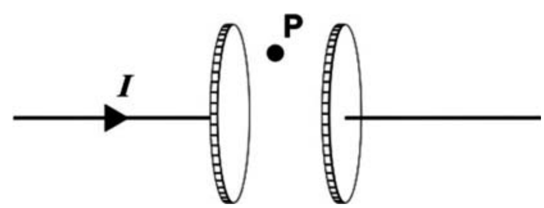


(18) An insulated wire is wound around one side of a piece of iron and the ends of the wire are connected to the terminals of a battery. A second insulated wire is wound around the other side of the piece of iron and its ends connected across a light bulb. A switch, which can be opened or closed, is inserted in the wire to the battery. Which of the following statements about this arrangement is true?



a. The bulb will light as long as the switch is closed.
b. The bulb never lights because the two wires are not connected since they are insulated.
c. The bulb lights momentarily only when the switch is first closed and not when it is opened.
d. The bulb will light momentarily anytime the switch is closed or opened.
e. The bulb never lights because there is no current in the iron piece.

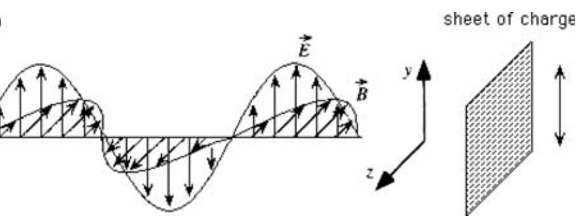
(19) As the capacitor shown below is charged with a constant current *I*, at point *P* there is a



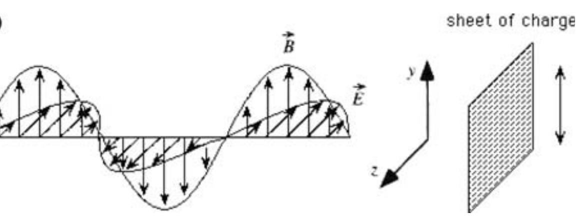
a. Zero electric and zero magnetic field
b. Constant electric field and zero magnetic field.
c. Constant magnetic field and zero electric field.
d. Changing electric field and constant magnetic field.
e. Changing magnetic field and constant electric field.

(20) An infinite sheet of positive charge in the yz plane (see figure below) is shaken up and down in the y direction. Which of the following is the correct representation of the electromagnetic wave generated to the left of the sheet of charge as a result of this shaking.

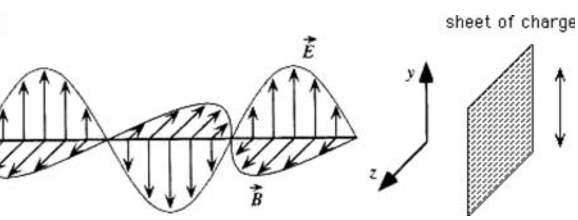
(a)



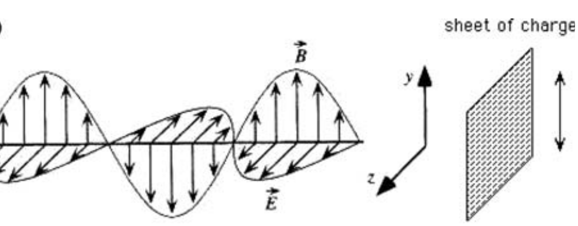
(b)



(c)

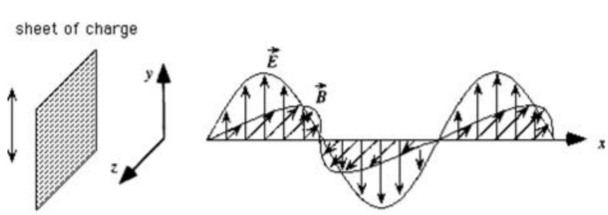


(d)

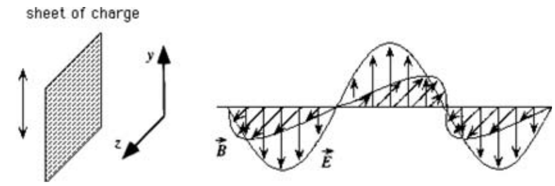


(e) None of these is correct.

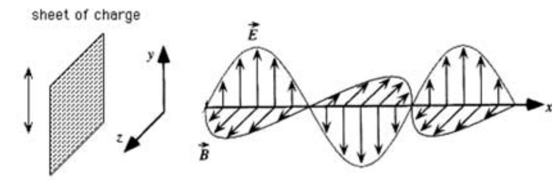
(21) A pulse of electromagnetic radiation is propagating to the left as shown below. It is incident on a highly conducting sheet in the yz plane, and is totally reflected by that sheet.



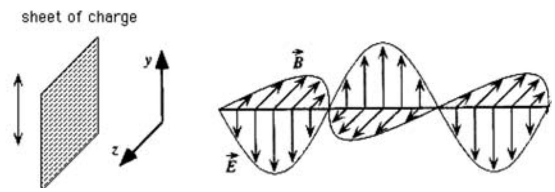
Which of the following is the correct representation of the reflected electromagnetic pulse caused by the incident pulse above, as seen at a later time, after the reflection.



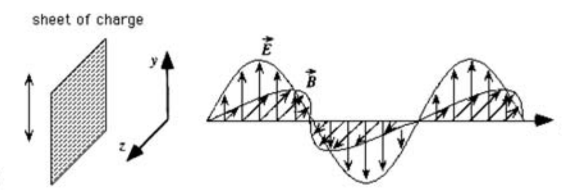
(a)



(b)



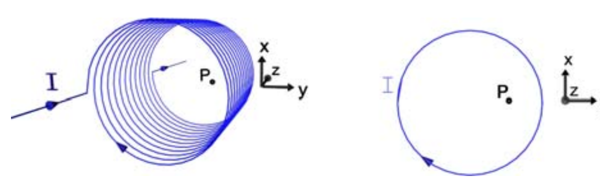
(c)



(d)

(e) None of the above.

(22) An inductor carries a current $I(t)$ which is increasing in time with. $dI(t)/dt$ = *positive constant*. The z-axis is into the page.

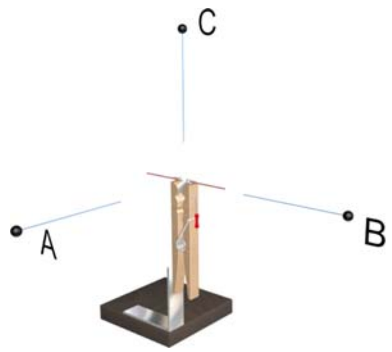


In which direction is the electric field at point P shown above?

(a) +x
(b) −x
(c) +z
(d) −z
(e) None of the above

(23) A quarter wave dipole antenna is oriented as shown below. The observations points *A*, *B*, and *C* are all located at the same distance from the center of the antenna. Let E_A be the amplitude (always

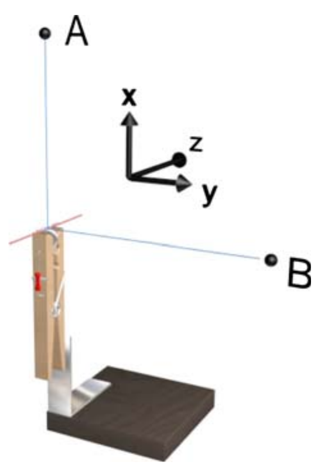
positive) of the radiation electric field at observation point A, and so on.



Which of the following is true

(a) $E_A = E_C = E_B$
(b) $E_A > E_C = E_B$
(c) $E_A = E_C > E_B$
(d) $E_A < E_C = E_B$
(e) None of the above

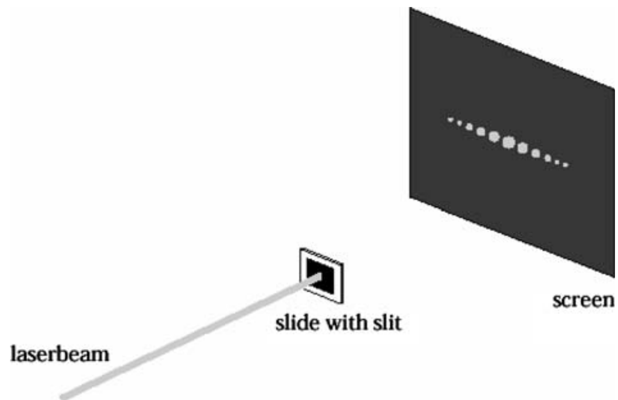
(24) A quarter wave dipole antenna is oriented as shown below. The observations points A and B are located as shown.



Which of the following statements is true about the radiation electric field **E** and magnetic field **B** field at these two observation points.

(a) **E** at A is in the + or $-z$ direction and **B** at B is in the + or $-x$ direction
(b) **E** at A is in the + or $-y$ direction and **B** at B is in the + or $-z$ direction
(c) **E** at A is in the + or $-z$ direction and **B** at B is in the + or $-z$ direction
(d) **E** at A is in the + or $-y$ direction and **B** at B is in the + or $-y$ direction
(e) None of the above.

(25) The pattern on the screen is due to a narrow slit that is



(a) Horizontal, because the diffraction occurs in the direction of the smallest dimension of the slit.
(b) Horizontal, because the diffraction occurs in the direction of the largest dimension of the slit.
(c) Vertical, because the diffraction occurs in the direction of the smallest dimension of the slit.
(d) Vertical, because the diffraction occurs in the direction of the largest dimension of the slit.
(e) In order to determine the direction of the slit, the refraction index of the screen is needed.

APPENDIX II

ELECTROMAGNETISM B
MIT DEPARTMENT OF PHYSICS

Instructions: Please circle the letter corresponding to the correct choice in your pink score sheet.

(1) 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, and we move the +Q and +4Q charges to be 3 times as far apart as they were:

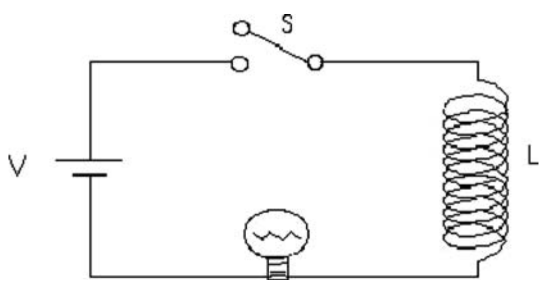
What is the magnitude of the force on the +4Q?

(a) F/9
(b) F/3
(c) 4F/9
(d) 4F/3
(e) None of the above.

(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.

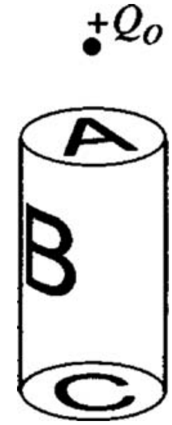
(3) The circuit below contains a battery, an inductor, a bulb and a switch. The switch is initially open as shown in the diagram.



Which correctly describes what happens to the bulb when the switch is closed?

(a) The bulb is dim and remains dim.
(b) At first the bulb is dim and it gets brighter and brighter until its brightness levels off at a constant level.
(c) The bulb is bright and remains bright.
(d) At first the bulb is bright and it gets dimmer and dimmer until it goes off.
(e) None of these is correct.

(4) The area vectors **dS** at each point on a closed surface (i.e., a surface that surrounds a volume) are always chosen to point *out of the enclosed volume*. A closed imaginary surface is called a Gaussian surface. The Gaussian surface below is a cylinder. A positive charge is located on the cylinder axis above the Gaussian cylinder, as shown below.



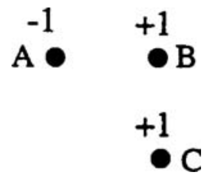
Which statement is correct about the flux $\oint \mathbf{E} \cdot \mathbf{dS}$ through surface B and through the entire closed surface A + B + C ?

(a) The flux through surface B is positive and through the entire closed surface it is positive.
(b) The flux through B is positive and through the entire surface it is negative.
(c) The flux through B is positive and the through the entire surface it is zero.
(d) The flux through B is negative and through the entire surface it is zero.
(e) The flux through B is negative and through the entire surface it is negative.

(5) A negative 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). What happens to the electric potential energy (in joules) of the negative charge, after the charge is released from rest in the uniform electric field?

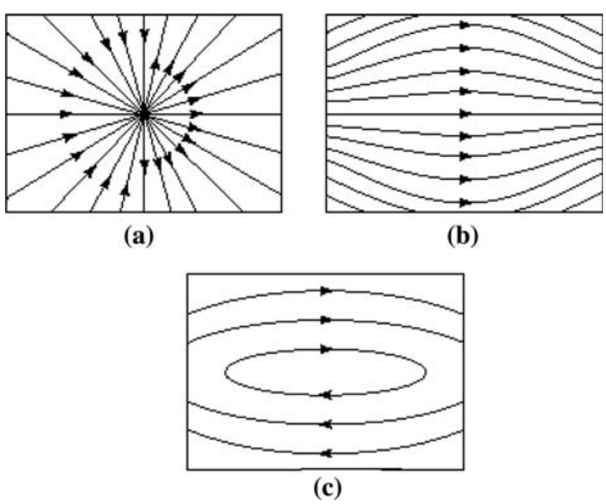
(a) It will remain constant because the electric field is uniform.
(b) It will remain constant because the charge remains at rest.
(c) It will increase because the charge will move in the direction of the electric field.
(d) It will decrease because the charge will move in the opposite direction of the electric field.
(e) It will decrease because the charge will move in the direction of the electric field.

(6) Three similar charged particles are placed one centimeter apart with the number of units of charge and the sign (+, −) of the charge indicated. Each charge is subject to electric forces caused by other charged particles.



Which of the arrows below *best* represents the direction (quadrant) of the net force on charge C?

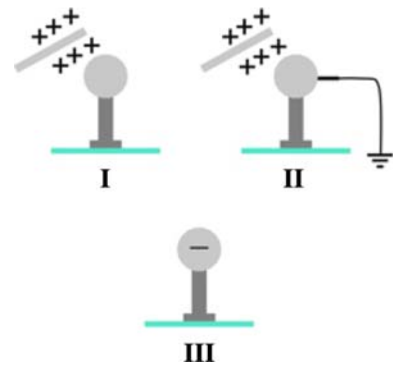
(7) Consider the three field patterns shown below.



Assuming there are no charges in the regions shown, which of the patterns represent(s) a possible electrostatic field:

(a) (a)
(b) (b)
(c) (c)
(d) (a) and (c)
(e) (b) and (c).

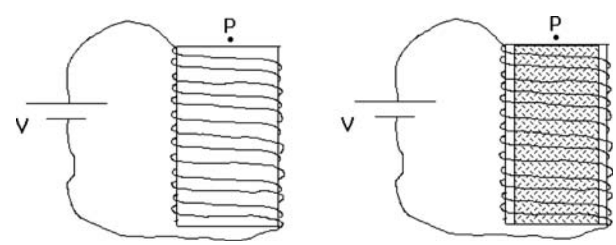
(8) A positively charged object is placed close to a conducting object attached to an insulating glass pedestal (I). After the opposite side of the conductor is grounded for a short time interval (II), the conductor becomes negatively charged (III).



Based on this information, we can conclude that within the conductor:

(a) Both positive and negative charges move freely.
(b) Only negative charges move freely.
(c) Only positive charges move freely.
(d) Neither positive nor negative charges move freely.
(e) More information is needed.

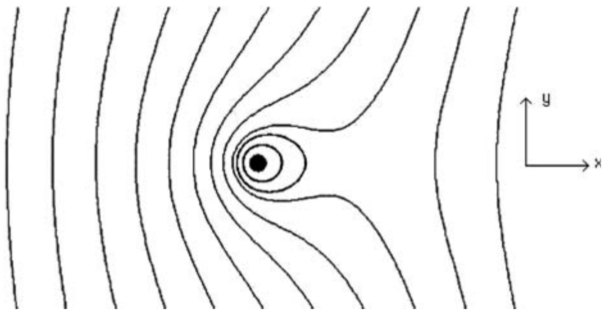
(9) The figure on the left below shows an inductor connected to a battery of fixed voltage *V*. The magnitude of the magnetic field at point P on the left is B_o. On the right, we have inserted a previously unmagnetized soft iron core into the inductor. Which of the following statements correctly describes the magnetic field at point P after the soft iron core is inserted?



(a) The field at P is in the same direction and its magnitude is greater than B_o.
(b) The field at P is in the same direction and its magnitude is smaller than B_o.
(c) The field at P is in the opposite direction and its magnitude is greater than B_o.
(d) The field at P is in the opposite direction and its magnitude is smaller than B_o.
(e) The field at P is unchanged.

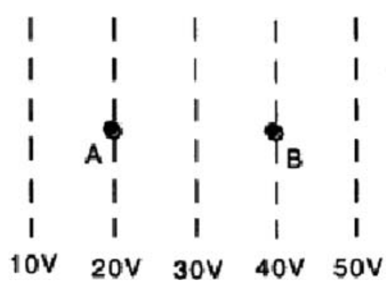
(10) The figure below shows the magnetic field lines (without arrows to indicate direction) of the

field of a constant magnetic field in the $+y$ or $-y$-direction plus that of a current carrying wire carrying current out of or into the page. Choose the description below that describes the force on the current.



(a) The force is to the left.
(b) The force is upwards.
(c) The force is to the right.
(d) The force is downward.
(e) More information is needed.

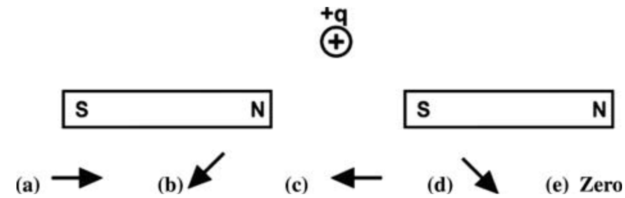
(11) In the figure below, the dashed lines show the equipotential lines of electric fields. (A charge moving along a line of equal potential would have a constant electric potential energy.) A charged object is moved directly from point A to point B. The charge on the object is $+1\ \mu$C.



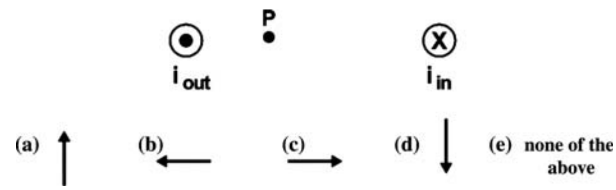
What is the direction of the electric force exerted by the field on the $+\ 1\ \mu$C charged object when at A and when at B?

(a) Right at A and right at B.
(b) Left at A and left at B.
(c) Left at A and right at B.
(d) Right at A and left at B.
(e) No electric force at either.

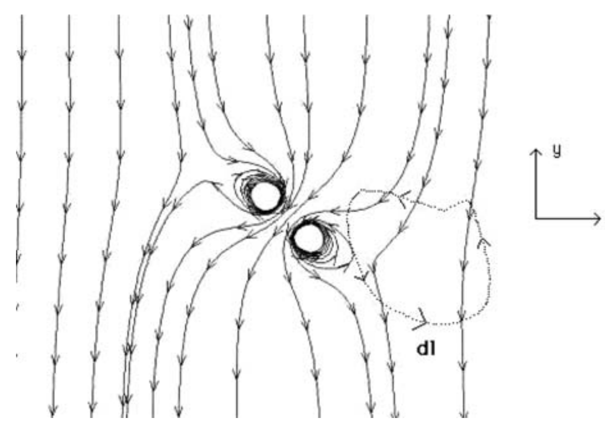
(12) A positively charged particle (+q) is at rest in the plane between two fixed bar magnets, as shown. Which choice below best represents the resultant MAGNETIC force exerted by the magnets on the charge?



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



(14) The figure below shows the magnetic field lines of a current carrying ring in a constant field. The currents that generate the constant field are very distant and are not shown. The dotted line represents a closed contour with the sense of **dl** as shown.



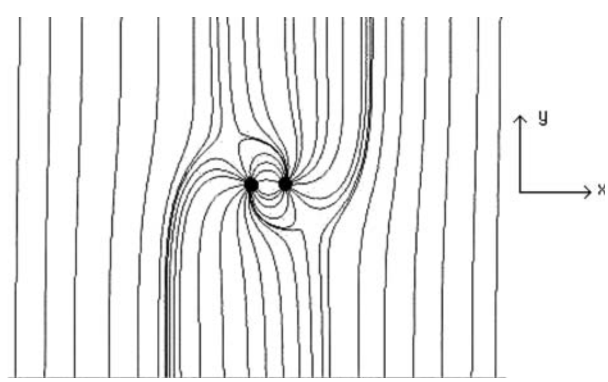
When we evaluate $\oint \mathbf{B} \cdot \mathbf{dl}$ around this closed contour, the result we find is:

(a) Non-zero and positive.
(b) Non-zero and negative.
(c) Zero
(d) More information is needed
(e) Indeterminate

(15) What happens to a positive charge that is placed at rest in a uniform magnetic field?

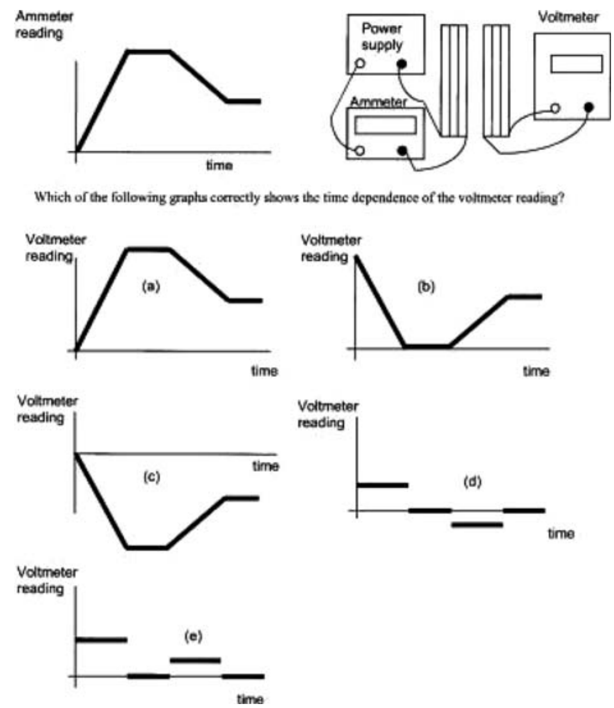
(a) It moves with constant velocity since the force has a constant magnitude.
(b) It moves with a constant acceleration since the force has a constant magnitude.
(c) It moves in a circle at a constant speed since the force is always perpendicular to the velocity.
(d) It accelerates in a circle since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

(16) The figure below shows the electric field lines (without arrows) for an electric dipole in a constant vertical electric field along the $+y$ or $-y$-direction. Choose the description below that describes the torque on the electric dipole.

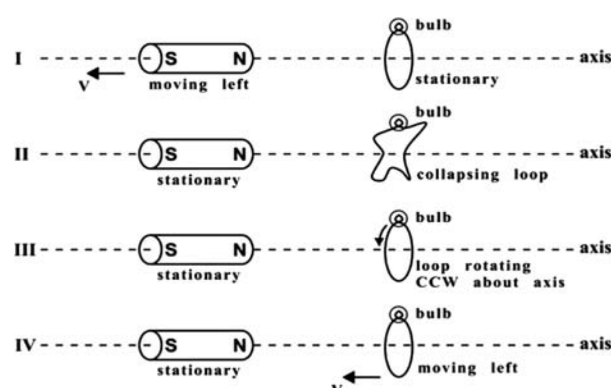


(a) The torque is such that the dipole will rotate clockwise.
(b) The torque is such that the dipole will rotate counterclockwise.
(c) The torque on the dipole is zero.
(d) More information is needed.
(e) None of the above.

(17) 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.



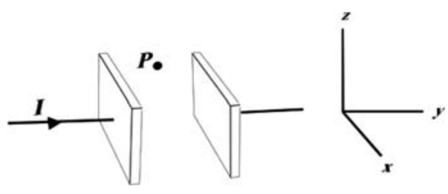
(18) These four separate figures involve a cylindrical magnet and a tiny light bulb connected to the ends of a loop of copper wire. The plane of the wire loop is perpendicular to the reference axis. The states of motion of the magnet and of the loop of wire are indicated in the diagram. Speed will be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



In which of the below figures will the light bulb be glowing?

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

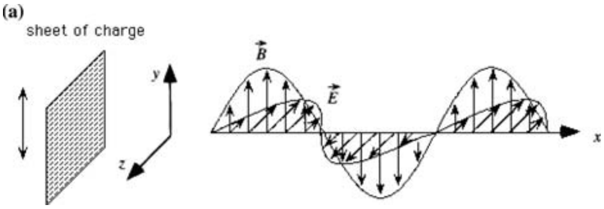
(19) A capacitor is charged by a steady current I. In which direction is the magnetic field at point P halfway between the top of the plates?



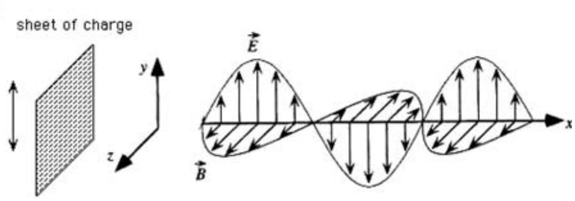
(a) +x
(b) −x
(c) +z
(d) −z
(e) None of the above

(20) An infinite sheet of positive charge in the yz plane (see figure) is shaken up and down in the y direction. Which of the following sketches is a possible representation of the electromagnetic wave generated to the right of the sheet as a result of this shaking.

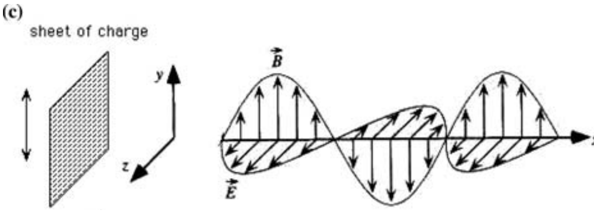
(a)



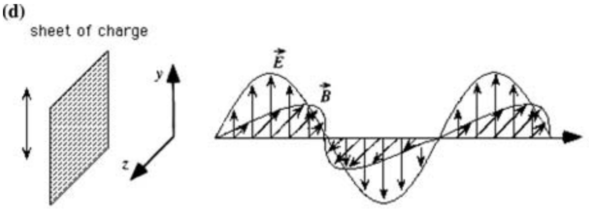
(b)



(c)

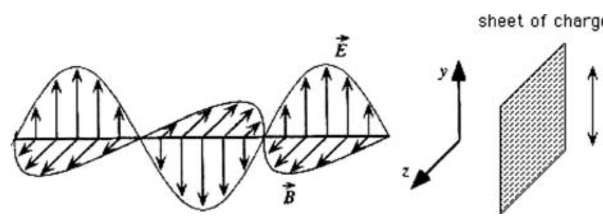


(d)

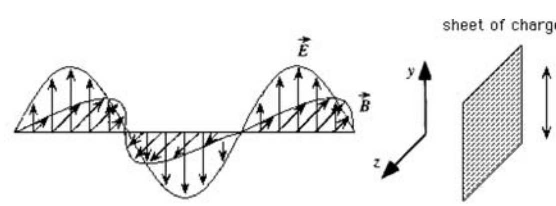


(e) None of the above.

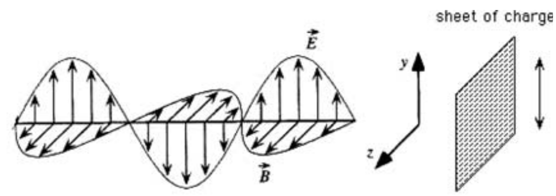
(21) A pulse of electromagnetic radiation propagating to the right is shown below. It is incident on a highly conducting sheet in the yz plane, and is totally reflected by that sheet.



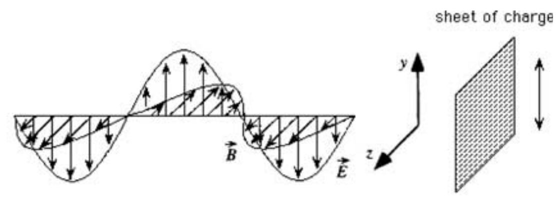
Which of the following is the correct representation of the reflected electromagnetic pulse caused by the incident wave above, as seen at a later time, after the reflection.



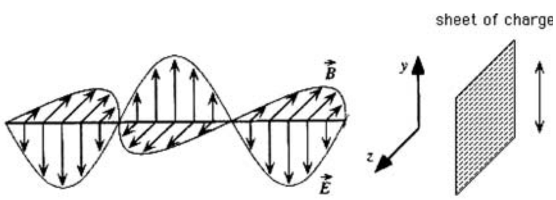
(a)



(b)



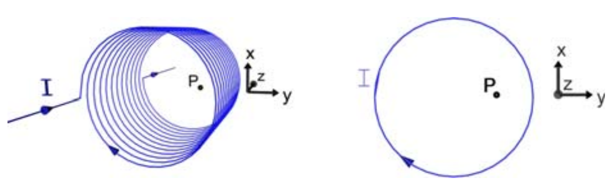
(c)



(d)

(e) None of these is correct.

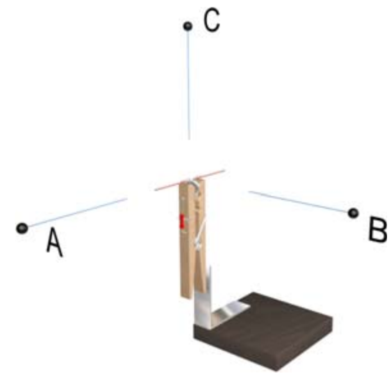
(22) The inductor shown below has a current I(t) running through it which is increasing at a constant rate, i.e. dI(t)/dt = positive constant. The z-axis is into the page.



At point P there is a

(a) Zero electric and zero magnetic field.
(b) Constant electric field and zero magnetic field.
(c) Constant magnetic field and zero electric field.
(d) Changing electric field and constant magnetic field.
(e) Changing magnetic field and constant electric field.

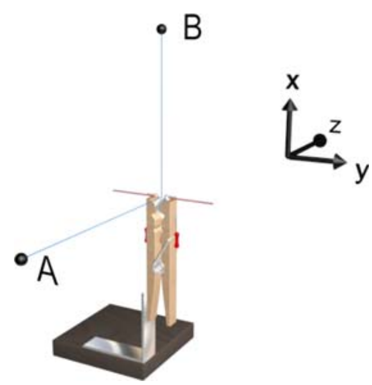
(23) A quarter wave dipole antenna is oriented as shown below. The observations points A, B, and C are all located the same distance from the center of the antenna. Let E_A be the amplitude (always positive) of the radiation electric field at observation point A, and so on.



Which of the following is true

(a) $E_A = E_C = E_B$
(b) $E_A > E_C = E_B$
(c) $E_A = E_C > E_B$
(d) $E_A < E_C = E_B$
(e) None of the above

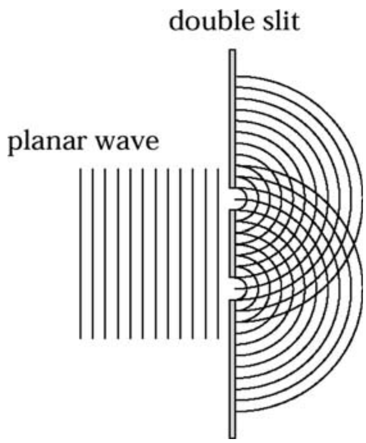
(24) A quarter wave dipole antenna is oriented as shown below. The observations points A and B are located as shown. Let E_A be the amplitude (always positive) of the radiation electric field at observation point A, and so on.



Which of the following statements is true about the radiation electric field **E** and magnetic field **B** field at these two observation points.

(a) **E** at A is in the + or $-y$ direction and **B** at B is in the + or $-y$ direction
(b) **E** at A is in the + or $-y$ direction and **B** at B is in the + or $-z$ direction
(c) **E** at A is in the + or $-x$ direction and **B** at B is in the + or $-z$ direction
(d) **E** at A is in the + or $-x$ direction and **B** at B is in the + or $-y$ direction
(e) None of the above

(25) A planar wave is incident on a pair of slits as shown.



Seen on a screen behind the slits are

(a) Many spots of varying intensity, distributed evenly.
(b) Many spots of varying intensity, distributed randomly.
(c) Many spots of equal intensity, distributed evenly.
(d) Many spots of equal intensity, distributed randomly.
(e) Two spots, one behind each slit.

REFERENCES

Arzi, H. J. Ben-Zvi, R. and Ganiel, U. (1985). Proactive and retroactive facilitation of long-term retention by curriculum continuity. *American Educational Research Journal* 22(3): 369–388.

Barufaldi, J. P., and Spiegel, G. F., Jr. (1994). The effects of a contribution of text structure awareness and graphic postorganizers on recall and retention of science knowledge. ERIC Publication EJ498237.

Beichner, R., Dori, Y. J., and Belcher, J. W. (2006). New physics teaching and assessment: laboratory- and technology-enhanced active learning. In J. J. Mintzes and W. H. Leonard (Eds.), *Handbook of College Science Teaching: Theory, Research and Practice*, (pp. 97–106) NSTA Press, Washington, DC, USA, Chapter 10.

Cummings, K., Marx, J., Thornton, R., and Kuhl, D. (1999). Evaluating innovations in studio physics. *Physics Educational Research, American Journal of Physics Suppl.* 67: S38–S45.

Dori, Y. J., and Belcher, J. W. (2005a). How does technology-enabled active learning affect undergraduate students' understanding of electromagnetism concepts?. *The Journal of the Learning Sciences* 14(2): 243–279.

Dori, Y. J., and Belcher, J. W. (2005b). Learning electromagnetism with visualizations and active learning. In J. K. Gilbert (Ed.), *Visualization in Science Education* (pp. 187–216). Dordrecht, The Netherlands: Springer.

Dori, Y. J., Belcher, J. W., Bessette, M., Danziger, M., McKinney, A., and Hult, E. (2003). Technology for active learning. *Materials Today* 6(12): 44–49.

Dori, Y. J., and Sasson, I. (2008). Chemical understanding and graphing skills in an honors case-based computerized chemistry laboratory environment: The value of bidirectional visual and textual representations. *Journal of Research in Science Teaching*, 45(2), in press.

Frank, M. (2006). How to teach using today's technology: Matching the teaching strategy to the E-learning approach. In L. Tan, W. Hin, & R. Subramaniam (Eds.), *Handbook of Research on Literacy in Technology* (pp. 372–393). Hershey, PA: Idea Group Publishing.

Frank, M., and Elata, D. (2005). Developing the Capacity for Engineering Systems Thinking (CEST) of freshman engineering students. *Journal of Systems Engineering* 8(2): 187–195.

Hake, R. R. (1998). Interactive-engagement versus traditional methods: A six-thousand-students-survey of mechanics test data for introductory physics courses. *American Journal of Physics* 66: 67–74.

Halpern, D. F., and Hakel, M. D. (2003). Applying the science of learning to the university and beyond: Teaching for long-term retention and transfer. *Change*, July/August: 36–41.

Handelsman, J., Ebert-May, D., Beichner, R., Bruns, P., Chang, A., DeHaan, R., Gentile, J., Lauffer, S., Strwart, J., Tilghman, S., and Wood, W. (2004). Scientific teaching. *Science Magazine* 304: 521–522.

Leonard, W. H. (1987). Dose the presentation style of question inserted into text influence understanding and retention of science concepts?. *Journal of Research in Science Teaching* 24: 27–37.

Leonard, W. H., and Lowery, L. F. (1984). The effects of question types in textual reading upon retention of biology concepts. *Journal of Research in Science Teaching* 21: 377–384.

Lewalter, D. (2003). Cognitive strategies for learning from static and dynamic visuals. *Learning and Instruction* 13(2): 177–190.

Lowe, R. K. (2003). Animation and learning: selective processing of information in dynamic graphics. *Learning and Instruction: The Journal of the European Association for Research on Learning and Instruction* 13(2): 157–176.

Maloney, D. P., O'Kuma, T. L., Hieggelke, C. J., and Heuvelen, A.Van (2001). Surveying students' conceptual knowledge of electricity and magnetism. *American Journal of Physics – Suppl* 69: S12–S23.

Martenson, D., Eriksson, H., and Ingelman-Sundberg, M. (1985). Medical chemistry: Evaluation of active and problem-oriented teaching methods. *Medical Education* 19: 34–42.

Mayer, R. E. (2002). Cognitive theory and the design of multimedia instruction: An example of the two-way street between cognition and instruction. In D. F. Halpern & M. D. Hakel (Eds.), *Applying the science of learning to university teaching and beyond* (pp. 55-72). San Francisco: Jossey-Bass.

Mazur, A. (1997). *Peer Instruction*, Prentice Hall, Upper Saddle River, NJ.

McDermott, L. C. (1991). Millikan lecture 1990: What we teach and what is learned – closing the gap. *American Journal of Physics* 59: 301–315.

McDermott, L. C., and the Physics Education Group at the University of Washington. (1996). Physics by Inquiry, Volumes I & II. John Wiley & Sons, Inc., New York.

Novak, J. D., Ring, D. G., and Tamir, P. (1971). Interpretation of research findings in terms of Ausubel's theory and implications for science education. *Science Education* 55(4): 438–526.

Otto, P. B., and Schuck, R. F. (1983). The effects of teacher questioning strategy training program on teaching behavior, student achievement and retention. *Journal of Research in Science Teaching* 20: 521–528.

Redish, E. F., Saul, J. M., and Steinberg, R. N. (1997). On the effectiveness of active-engagement microcomputer-based laboratories. *American Journal of Physics* 65: 45–54.

Sokoloff, D. R., and Thornton, R. K. (1997). Using interactive lecture demonstrations to create an active learning environment. *The Physics Teacher* 35: 340–347.

Schnotz, W., and Lowe, R. (2003). Introduction. *Learning and Instruction* 13(2): 117–124.

Tamir, P., and Amir, R. (1981) Retrospective curriculum evaluation: an approach to the evaluation of long term effects. *Curriculum Inquiry* 11: 249–278.