Using Conceptual Questions in Electromagnetics Education

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The topic of electromagnetics is rather difficult for students to grasp and for instructors to teach. On the other hand, its importance to technical education can hardly be overstated. This article addresses some of the challenges in the methodology and practice of electromagnetics teaching and learning in general and in particular related to the conceptual understanding of the material and associated concept-based electromagnetic problem-solving skills. It introduces, frames, and discusses some possible uses of conceptual questions. These are multiple-choice questions requiring conceptual reasoning and understanding and very little or no calculations in electromagnetics education. We discuss applications of conceptual questions to modalities of active teaching/learning, such as a flipped classroom, and different types of assessments of student learning and teaching outcomes. Conceptual questions of this scope and intent are new in electromagnetics education and likely in any electrical and computer engineering area.

EDITOR'S NOTE

Sean Hum

This issue's "Education Corner" column discusses the idea behind and application of conceptual questions in engineering electromagnetics education. As Prof. Notaroš details in this article, these qualitatively focused questions can help students grasp difficult electromagnetic concepts without needing to first delve into the detailed mathematical formalism behind them, which we all are aware can form a significant initial impediment to students. As such, conceptual questions can be used in a variety of ways to promote a deeper understanding of electromagnetic theory and the key ideas behind them. They certainly appear to be a promising tool that can be combined with various modes of instruction to help students form stronger foundations in electromagnetics.

INTRODUCTION

Electromagnetic theory, or the theory of electromagnetic fields and waves, is a fundamental underpinning of technical education, but, at the same time, it is often perceived as the most challenging and demanding course in the electrical engineering curriculum. This material is extremely abstract and mathematically rigorous and intensive. Students find it rather difficult to grasp, and instructors also find it a difficult subject to teach. This is not unique to any particular school or department, country, or geographical region of the world [1]–[4]. On the other hand, the importance of electromagnetics as a fundamental science and engineering discipline to technical education can hardly be overstated.

In addition, electromagnetic theory has immediate impacts on a great variety of cutting-edge applications in antenna, propagation, microwave, radar, microelectronics, and lightwave technologies. A comprehensive knowledge and firm grasp of electromagnetic fundamentals are essential for students in a number of undergraduate and graduate courses as well as for engineering graduates as they join the workforce, now and in the future.

This article is aimed at providing a contribution to the ongoing discussion of problems and challenges in the methodology and practice of teaching undergraduate electromagnetics courses and student learning in these courses (e.g., [5] and [6]) by addressing students' conceptual understanding of the material

Digital Object Identifier 10.1109/MAP.2021.3069218
Date of current version: 2 June 2021

and related concept-based electromagnetic problem-solving skills. In undergraduate electromagnetics classes, students usually get overwhelmed by the abstract, dry, and overly complicated mathematical formalisms involved in theoretical derivations and problem solutions related to the analysis of electromagnetic fields, waves, devices, and systems.

While doing their best and attempting to solve problems, understand derivations, and perform studies, the students will very often admit that, while more or less successfully handling the equations, they, in fact, do not have an idea of what is actually going on in their analysis or computation. That is, they do not satisfactorily understand the basic concepts behind the theory, derivations, computations, and applications and are not able to carry out conceptual, strategic, and qualitative analyses of problem situations or application contexts prior to performing the quantitative analyses and calculations. Because of the lack of understanding, in many cases, the students soon lose confidence. After that, they lose motivation, and the whole learning process is sooner or later reduced to frantically browsing through textbook pages or online resources in a quest for a suitable final formula or set of formulas that look applicable and are to be applied in a nearly random fashion.

This article proposes the utilization of conceptual questions in electromagnetics education. Conceptual questions are multiple-choice questions that focus on the core concepts of the material, requiring conceptual reasoning and understanding and very little or no calculations. However, these questions are aimed at strongly enforcing and enhancing both the theoretical concepts and understanding and problem-solving techniques and skills in electromagnetics in conjunction with the computational problems.

Conceptual questions have been broadly used and discussed in other disciplines of science and engineering. In introductory physics, peer instruction is a widely used pedagogy in which lectures are interspersed with short conceptual questions (ConcepTests) designed to reveal common misunderstandings and to actively engage students in lecture courses [7]. There has been extensive discussion in the physics teaching community on designing effective questions for classroom response system teaching [8]. The process of developing a robust concept inventory for heat transfer, fluid mechanics, and thermodynamics, from identifying the key concepts in a field through developing multiple-choice questions and believable distracters to validity and reliability testing, is described in [9].

A study in chemistry teaching compares students' experiences with two forms of conceptual questions, a pictorial form, which expresses information pictorially or graphically, and a verbal form, which uses written words without pictures for describing the problem or situation [10]. Within biochemistry and molecular biology curricula, a discussion has emerged of the challenges in measuring and developing a conceptual understanding that requires competence in the cognitive skills of mindful memorization, integration, transfer, analogical reasoning, and system thinking [11].

An interesting review of the fundamental issues in conceptual knowledge and learning within engineering science appears in [12]. An investigation into the conceptual understanding of dc circuit theory of first-year electrical engineering students indicates that misconceptions are robust and pervasive, crossing institutional and national boundaries [13]. A study in civil engineering explores the differences in the conceptual understanding of statics across engineering students and professional engineers [14]. Another study finds that misconceptions related to temperature, heat, and energy among undergraduate engineering students are both prevalent and resistant to change through standard instruction [15].

An example of how remote-control personal response systems can be applied to an introductory materials science course using conceptual questions is presented in [16]. Experiences with an electronic classroom communication system with formative assessment on a regular basis in biomechanics classrooms show that this approach can help instructors reduce the variance in students' conceptual understanding of fundamental concepts early in the course, allowing for more uniform coverage of advanced topics later in the course [17].

A discussion of different inductive teaching methods in [18] includes a description of just-in-time teaching, where students respond electronically to conceptual questions before each class, and the instructor adjusts the lesson to react to misconceptions revealed by students' responses; the article also includes a review of the effectiveness of this approach in physics, biology, and chemistry instruction. An example of using conceptual questions in graduate education is an active radio frequency circuits course at Tampere University of Technology, Finland, which included weekly prelecture assignments, concept tests, and student seminar presentations [19].

This study refers to a recently developed unique and extremely comprehensive collection of conceptual questions in electromagnetics [20] (note that a large collection of conceptual questions also appears in [21] as an online supplement). We present and discuss several illustrative examples of conceptual questions along with the associated common student misconceptions. The article introduces, frames, and discusses some possible uses of conceptual questions in teaching and learning electromagnetics within the frameworks of active teaching/learning, such as interactive class discussions and the flipped classroom, and formative class assessments, including the assessment of class prework to motivate preassigned reading, accreditation compliance, and using conceptual questions for homework and exams.

CONCEPTUAL QUESTIONS FOR ELECTROMAGNETICS EDUCATION

Conceptual questions are meant and designed to both evaluate and enhance students' understanding of core electromagnetic concepts with very little or no calculations [20]. They are also intended to enforce the associated concept-based electromagnetic problem-solving skills, which are then utilized in computational problems [21]. The multiple potential answers for each question are designed to emphasize a true understanding of the material as well as to identify severe misconceptions. Some of the incorrect answers provided for each question are designed to serve as distractors of different types, which are meant to identify common misconceptions and errors by learners and to simply draw a student with no or poor understanding of the concept away from the correct choice (that might otherwise be selected as a random guess).

Conceptual questions are also designed to help students actively integrate conceptual knowledge into the problem-solving process. Indeed, these questions are most effective when used in conjunction with computational problems to help students develop problem-solving strategies based on conceptual analysis. Many of the conceptual questions require the student to perform conceptual, strategic, and qualitative analyses of problem situations, skills that are of significant and immediate assistance when performing the quantitative analyses and calculations required in standard computational problems. Without a conceptual knowledge structure to which they can be tied, equations are meaningless and quickly forgotten.

For example, conceptual questions can help the students envision a possible solution path and can guide the solution process in terms of what fundamental physical law or principle mathematical equations should be applied to solve the problem and how they should be applied, and then the associated computational examples and problems elaborate on the execution of the solution strategy and equations. Note that the former part is most frequently the most critical part of the solution to the students. Often, some students are very good at executing the solution strategy and equations, but they are executing the "wrong" strategy and inappropriate equations and are actually computationally analyzing (perhaps perfectly) an unphysical problem or, at best, the "wrong" (different) problem. Similarly, some students never get to the latter part of the problem–solution process, namely, to the computational execution stage, because they cannot sort out the concepts and set up the solution strategy and the main steps of the solution.

When designing or choosing the computational problems for mixed use with conceptual questions, and generally as well (in this author's opinion), it is best to focus on the examples and problems that emphasize physical conceptual reasoning and mathematical synthesis of solutions and not pure formulaic ("plug-and-chug") solving [21]. Such conceptual problems should provide opportunities for students to further develop and reinforce their conceptual understanding of the material and true electromagnetic problem-solving skills. By acquiring such skills, which are definitely not limited to skillful browsing through textbook pages in a quest for a suitable "black-box" formula or set of formulas nor a skillful use of pocket calculators to plug-and-chug, the students also acquire true confidence and pride in electromagnetics and a strong appreciation for both its theoretical fundamentals and its practical applications.

Conceptual questions and concept-driven computational problems in tandem are aimed at developing and fully understanding electromagnetic problem-solving strategies and techniques, not just using formulas. To help the students develop such skills, "recipes" for electromagnetic field and wave computations, rather than formulas, and the associated problem-solving hints are systematically introduced and enforced using both resources [20], [21]. In this context, it also is better, in the author's opinion, not to use too many of the problems that carry dry and overcomplicated pure mathematical formalisms as such problems tend to be extremely poorly received and not appreciated by students and often do not contribute significantly, or directly enough, to a conceptual understanding of the material and to engineering problem-solving skills. The primary goal is to teach the students to reason through different (more or less challenging) situations and help them gain confidence and really understand and like the material.

It is also essential to include computational examples and problems as well as conceptual questions that have a strong realistic engineering context [20], [21]. This will increase students' motivation to learn and an appreciation of the practical relevance of the material. One goal of both the conceptual questions and concept-based computational problems is to connect abstract concepts to the real world of engineering and to put learning in context and illustrate the societal relevance of electromagnetics knowledge. Overall, both resources are a part of the general pedagogical approach to electromagnetics teaching and learning, emphasizing "electromagnetic thinking" in addressing and solving realistic electromagnetic problems and understanding and appreciating electromagnetic applications.

Moreover, conceptual questions may be very effectively combined with MATLAB computer exercises, tutorials, and projects in electromagnetics [22], [23]. On the one hand, MATLAB exercises can help the students develop a stronger intuition and a deeper understanding of electromagnetic concepts, especially the most abstract concepts that are the hardest to grasp and visualize. This is a prerequisite for reaching other (higher) categories of learning, including analyzing, evaluating, and creating. Through MATLAB-based computer-mediated exploration and inquiry, students can also invoke and enhance their electromagnetic conceptual thinking about and dealing with electromagnetic fields and waves by exploring various "what ifs" and bridging the fundamental concepts and practical applications without being overwhelmed with the abstract and often overly complicated and dry mathematics of analytical solutions.

On the other hand, when the students are introduced to MATLAB programming of electromagnetic fields and waves (in addition to demonstrations and visualization of electromagnetic phenomena), conceptual reasoning and understanding of the material developed and solidified through conceptual questions are essential for MATLAB programming of electromagnetics performed by students. In fact, the benefit of writing computer code is that it increases the students' need to understand the fundamental field and wave concepts of the problem involved as well as the need to be able to obtain the conventional analytical solutions of simple problems [24].

Several illustrative examples of conceptual questions within different subject topics of electromagnetics are displayed in Figures 1–5. Along with the questions and multiple-choice answers, the figures outline common misconceptions and provide a graphical and/or textual presentation of the underlying concepts and equations.

In terms of grading tests, exams, and homework, it is, of course, much easier and faster to grade multiple-choice questions than traditional computational problems. Moreover, because the questions are conceptual, choosing a wrong answer normally does not mean a simple error in computation but a misunderstanding of a concept or a major conceptual error regarding an equation or a solution procedure. Consequently, tests with conceptual questions can indeed be graded and the knowledge assessed on an on/off (correct/incorrect) basis considering only the provided answer choice and not the full work. In addition to being efficient, such grading is the fairest and most objective, and it eliminates the need for any discussions and interpretations of the student's work on the test.

Of course, the whole process can be tied to the available classroom (and other) technology, which can make it both very efficient and appealing to students. It is also well suited for incorporation into an existing virtual (electronic) learning management system. Students (and instructors) can access the questions through any computer or mobile device, e.g., smartphone, compatible with the online tool. In addition, technology-based tools allow the instructor to prompt students to provide written responses to justify the selection of the multiple-choice answer that they have chosen, which may have a positive influence on their answer choices [25]. Finally, because of their conceptual ("quickly and straight to the point") philosophy and effective multiple-choice format, conceptual questions may be useful for distance learning, online courses, and other forms of nontraditional course delivery.

Conceptual questions follow the intent and form of the questions on the Electromagnetics Concept Inventory (EMCI) tool [26]. The EMCI is an assessment tool for measuring students' understanding of fundamental concepts in electromagnetics developed within the National Science Foundation's Foundation Coalition project [27]. The EMCI is motivated by the Force Concept Inventory (FCI) assessment tool, created by Hestenes and Halloun to measure conceptual understanding of Newtonian mechanics [28]. Following the lead of the FCI and supported by the Foundation Coalition, faculty members have created concept inventories for several engineering disciplines, which include the Signals and Systems Concept Inventory, Thermodynamics Concept Inventory, Strength of Materials Concept Inventory, Circuits Concept Inventory, Fluid Mechanics Concept Inventory, and Materials Concept Inventory [27].

Conceptual Questions: Example 1

CONCEPTUAL QUESTION 4.17 **Different contours around the same conductor.** Consider two identical cylindrical metallic conductors carrying steady currents of the same intensity and Amperian contours positioned around each of them. The first contour is circular, while the other one has a square shape, as shown in Figure 4.15. The circulation of the magnetic flux density vector along the circular contour is

(A) larger than (B) the same as (C) smaller than

that along the square contour.

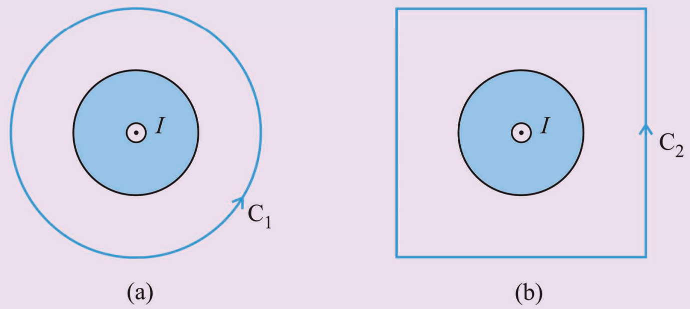
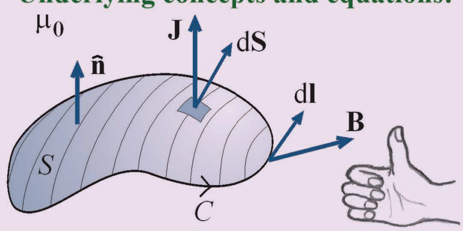


Figure 4.15 Contours of circular (a) and square (b) shapes outside cylindrical conductors carrying steady currents of the same intensity; for Conceptual Question 4.17.

A common misconception: The line integral of the magnetic field **B** in Ampère's law depends on the size of the surface area *S* enclosed by the contour *C*.

Underlying concepts and equations:



$$\oint_C \mathbf{B} \cdot d\mathbf{l} = \mu_0 \int_S \mathbf{J} \cdot d\mathbf{S},$$

What only matters is the total current *I* enclosed by the contour *C*, no matter the shape and size of *C*.

FIGURE 1. Example 1 of a conceptual question in electromagnetics [20] dealing with magnetic fields, along with an outline of a common misconception and the underlying concepts and equations [21]. The correct answer is (B).

The development of questions for concept inventories is a true research undertaking, going through many iterations and versions of the inventory and encompassing many years of development and calibration. This may include interviews of students to probe their misconceptions, collaboration among many instructors, and administering the tool at many institutions to a large number of students. The ultimate outcome is a nationally and internationally calibrated, accepted, and established standard assessment tool for the course or the discipline, with established and validated performance norms and statistics over many institutions and many years of testing, the most notable example of such an established assessment tool being the FCI.

Collections of conceptual questions for any pedagogical purpose, including the collection that is subject of this article, can, in principle, be created using the same research approach as the questions on a concept inventory. Generally, in good conceptual questions, if the students understand the concepts tested, they can easily choose the correct answer, whereas the students with poor understanding of the concepts will typically choose distractors, i.e., incorrect answers designed to embody common student misconceptions. Both the former and the latter features of good conceptual questions can be achieved by the previously outlined research and/or based on the pedagogical experience of the question developer. Both approaches have been used in the development of conceptual questions presented in this article, with the latter approach being dominant.

Ideally, all conceptual questions would have been created invoking the same rigor and completeness of design, testing, evaluation, validation, and calibration as the questions on a concept inventory. However, while the concept inventories typically have about 20 questions, the collection of conceptual questions considered here is orders of magnitude larger, containing about 1,000 multiple-choice questions. Whereas the improvement of all of the questions is a constant work in progress based on testing, validation, and feedback from students and instructors, they will, looking at the entire collection, naturally never be as thoroughly and meaningfully designed, tested, evaluated, validated, and calibrated as concept inventory questions.

SOME POSSIBLE USES OF CONCEPTUAL QUESTIONS IN TEACHING AND LEARNING ELECTROMAGNETICS

Pedagogically, conceptual questions are an invaluable resource. They can be used by instructors for innovative lecturing and in-class and homework assignments and testing, including online instruction and distance education, and by students for independent learning. The questions can be given for homework and on exams as well as in course lectures. Class presentations based on conceptual questions can be combined with traditional lecturing with different relative proportions.

Conceptual questions are also ideal for interactive in-class questions, explorations, and discussions (active teaching and learning [29]), for student-to-student interaction and students teaching

Conceptual Questions: Example 2

CONCEPTUAL QUESTION 1.13 **Field maximum from a potential distribution.** The electrostatic potential V in a region is a function of the rectangular coordinate x only, and $V(x)$ is shown in Figure 1.13. Consider the electric field intensities at points A, B, C, D, and E. The largest field intensity is at point

(A) A. (B) B. (C) C. (D) D. (E) E.

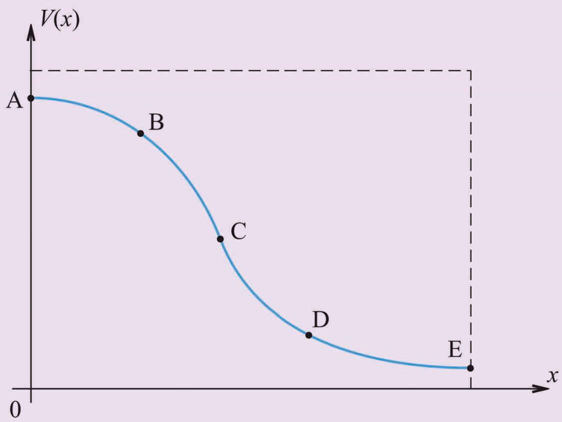


Figure 1.13 One-dimensional potential distribution; for Conceptual Question 1.13.

A common misconception: The field is strongest where the potential or voltage is highest.

Underlying concepts and equations:

$$\mathbf{E} = -\,\mathrm{grad}\,V = -\nabla V,$$

$$E_x = -\frac{\mathrm{d}V}{\mathrm{d}x}.$$

The field is proportional to the slope of the potential curve.

FIGURE 2. Example 2 of a conceptual question in electromagnetics [20] dealing with electric fields, along with an outline of a common misconception and the underlying concepts and equations [21]. The correct answer is (C).

one another (peer instruction [7], [30]), and for teamwork and exchange of ideas (collaborative teaching/learning [31]). Generally, all of these pedagogical techniques and approaches have recently gained a lot of attention from educators in science and engineering and are paving their way as a preferred mode, or a major component, of class delivery and instruction. Multiple studies and classroom experiences across science and engineering have indicated that these novel learner-centered pedagogies and practices, active teaching/learning in particular, are very effective, motivational, and positively evaluated by students [29], [31]–[35].

In addition, conceptual questions are perfectly suited for formative class assessment, namely, to assess student performance and evaluate the effectiveness of instruction as well as the success of programs and curricula, which are especially important in light of ABET [36] and similar accreditation criteria. The key word in these criteria is "assessment."

For instance, one of the many possibilities of active learning and peer instruction using this material would imply posing a conceptual question to the class, taking a "vote" on it, and then having a discussion of different answers and approaches, ideally with a resolution of disagreements between students within groups of peers (in the spirit of Eric Mazur's "peer instruction" in introductory physics [7], [30]). The students and the instructor discuss why some (incorrect) answers appeared attractive and seemed right and ultimately what is (or should be) the reasoning behind choosing the one correct answer.

Additionally, this material may align very well with a teaching approach constituting an inverted or flipped classroom [32], [37]–[39], where students' preliminary learning of the content occurs outside of the classroom by reading the theory (from a textbook or lecture notes) or watching video lectures, which then frees up more face-to-face time in the classroom for active and problem-based learning using conceptual questions and problems.

An example of the use of conceptual questions within a partially flipped classroom instruction approach is the implementation of conceptual quizzes to assess class prework and enhance student engagement in the ECE 341 Electromagnetic Fields and Devices I and ECE 342 Electromagnetic Fields and Devices II courses in the Department of Electrical and Computer Engineering at Colorado State University (CSU). The content of ECE 341 includes electrostatic fields in free space and in dielectrics, capacitance, electric energy, steady electric currents, magnetostatic fields in free space and in material media, electromagnetic induction, inductance, magnetic energy, slowly time-varying (quasistatic) electromagnetic fields, and general Maxwell's equations. ECE 342 covers rapidly time-varying electromagnetic fields, propagation of uniform plane electromagnetic waves in free space and in various media, wave reflection, transmission, and refraction, transmission-line theory using frequency- and time-domain analysis, rectangular metallic waveguides, and the fundamentals of radiation and antennas.

Conceptual Questions: Example 3

CONCEPTUAL QUESTION 1.31 **Electrostatic shielding – two bodies and a screen.** In order to protect body B from the electrostatic field due to a charged body A, an ungrounded closed metallic screen is introduced (Figure 1.27). The protection is achieved for

(A) case (a) only. (B) case (b) only. (C) both cases. (D) neither of the cases.

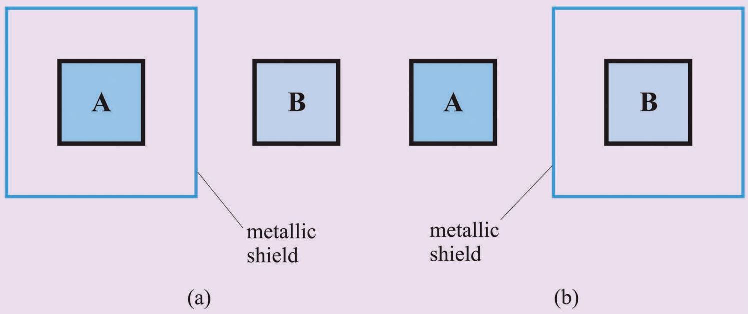


Figure 1.27 Two proposed configurations for electrostatic shielding; for Conceptual Question 1.31.

A common misconception: The generator of electrostatic interference should be caged, rather than the protected object.

Underlying concepts and equations:

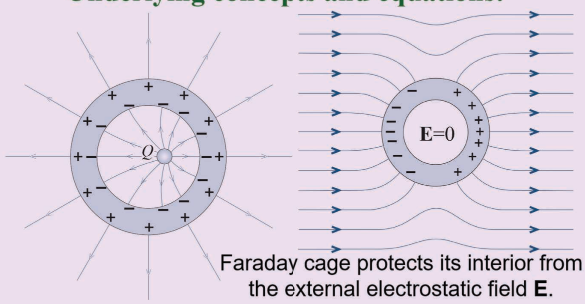


FIGURE 3. Example 3 of a conceptual question in electromagnetics [20] dealing with electrostatic shielding, along with an outline of a common misconception and the underlying concepts and equations [21]. The correct answer is (B).

This implementation included preassigned reading from [21], with prework assessment in the form of online interactive quizzes containing multiple-choice conceptual questions, for credit, administered through the learning management system Canvas, by Instructure [40], [41]. The conceptual question prework quizzes were used in ECE 341 during the Fall 2016 semester and the Fall 2017 semester and were implemented in ECE 342 in the Spring 2019 semester.

This particular use of conceptual questions is a part of a five-year "Revolutionizing Engineering and Computer science Departments" (RED) project at CSU, supported by the National Science Foundation. Within the CSU RED pedagogical model, the electrical engineering curriculum is no longer considered as a set of disparate courses taught by autonomous and isolated faculty but as an integrated system that fosters collaboration among faculty and students. The new organizational and pedagogical model emphasizes knowledge integration and interweaves thematic content threads throughout the curriculum [42].

The courses in the electromagnetics sequence have been integrated with the corresponding courses in the two-course sequences on signals/systems and electronics running in the same semester. Each of the courses is broken into a set of learning studio modules (LSMs), and the knowledge integration activities are created to help students grasp the commonality and correlations between core concepts across the curriculum [42]. Within the electromagnetics LSMs of the RED project, conceptual questions have been utilized for the assessment of class prework to motivate preassigned reading and enable a partially flipped classroom. To enable knowledge integration with the other two courses and the knowledge integration sessions (joint sessions of all three courses), the lecture time in the electromagnetics classes has been substantially reduced, and hence, there is an even greater need for intense, efficient, and productive engagement of students in the classroom prework, which has to be thoroughly designed and facilitated, and, most essentially, adequately assessed.

In preparation for each class, students must complete assigned prework that includes required reading and a timed, online quiz where they answer a series of carefully designed and chosen conceptual questions pertaining to topics in the preassigned reading within the current lecture material. The online prework assessment was done for credit to ensure that students read the material before coming to class [37]. A typical quiz had 10 conceptual questions, and the allotted time for the quiz was 1 h (although just a few minutes per question should be sufficient), taken by each student individually in Canvas at any time before the class. In fact, the time for a 10-question quiz averaged over all quizzes in the course and over all students taking the quiz for ECE 341 in the Fall 2016 semester was only 22.4 min. The average score on quizzes, averaged over all quizzes and all students, was 67.64%, and the quizzes were attempted by 80 students on average (out of 83 students in the class), so practically the entire class.

These brief, interactive formative assessments both evaluate and enhance student understanding of the core concepts of the reading material. Such gained understanding enables students to actively engage in the subsequent lecture class, taught in a flipped classroom fashion, primarily using realistic examples and problems that strongly reinforce the theoretical concepts and facilitate active and problem-based learning, including an interactive discussion. Although this procedure can be considered flipped, the class was actually only partially flipped because the lectures partially relied on the completed preassigned reading by the students and had a partial utilization of the associated interactive discussions [41].

In addition, only about one-half of the total number of class meetings followed this procedure, with the rest pertaining to knowledge integration sessions, exams, invited lectures, and other discussions. So, the conceptual questions of the class prework enabled the

Conceptual Questions: Examples 4,5

CONCEPTUAL QUESTION 7.52 **Radio communication in freshwater and salty lakes.** Due to the salt content, sea (salty) water is much more electrically conductive than fresh water. If a radio transmitter and a radio receiver are submerged in a lake, the communication is better for

(A) a freshwater lake. (B) a salty lake. (C) No difference.

CONCEPTUAL QUESTION 7.53 **Choice of frequency for radio communication with a submarine.** Out of the following, what is the most suitable frequency for radio communication with a submerged submarine?

(A) 1 kHz. (B) 10 kHz. (C) 100 kHz. (D) 1 MHz. (E) 10 MHz.

Common misconceptions: The more electrically conductive a medium the better RF propagation through it. The higher the frequency the better RF communication.

Underlying concepts and equations:

$$\delta \approx \frac{1}{\sqrt{\pi \mu f \sigma}},$$

Attenuation of electromagnetic waves in conducting media like sea water increases and propagation depth, δ, decreases with an increase in both conductivity of the medium, σ, and frequency of the wave, *f*.

FIGURE 4. Examples 4 and 5 of conceptual questions in electromagnetics [20] dealing with the propagation and attenuation of electromagnetic waves, along with an outline of common misconceptions and the underlying concepts and equations. The correct answer is (A) in both cases.

implementation of a partially flipped classroom, which, in turn, enabled the coverage of much more material with only about one-half of class time. To further solidify the understanding of the core concepts, similar conceptual questions were then given as part of the postwork homework assignment, along with computational problems based on these concepts.

The available results and analyses conducted indicate that this is a step in the right direction toward considerably improving students' learning, mastery, attitude, success, and satisfaction. Specifically, the percentage of students scoring at least 65% or higher on an exam was higher in the year with the new partially flipped classroom using conceptual questions for the assessment of class prework and enhancement of student engagement in electromagnetics LSMs on both the midterm exams and on the final exam (ECE 341, Fall 2016) when compared to the prior student performance when the same instructor taught the course traditionally.

A very substantial improvement in the overall course scores was also observed as well as a dramatic decrease in the D/F/W (nonpassing grades) rate (down to about 10% compared to about 25%) and an increase in the percent of the class that earned an A-level grade (up to 42% compared to about 26%) with the implementation of the partially flipped classroom in comparison with the electromagnetics classes taught traditionally (by the same instructor). All of the quantitative results and details of the evaluation and assessment of this approach can be found in [41].

Finally, the students' performances on the EMCI assessment instrument have shown a dramatic improvement. Namely, the instrument was administered as a posttest at the start of the Fall 2016 and the Fall 2017 semesters, respectively, to the seniors who studied electromagnetics in the previous academic year. The 2017 score by students learning electromagnetic fields in the Fall 2016 semester with the new partially flipped classroom utilizing conceptual questions for the assessment of class prework was 2.5 times higher than the score by students taught in the traditional manner.

So, the conceptual questions of the class prework enabled the implementation of a partially flipped classroom, which, in turn, enabled the coverage of much more material with only about one-half of class time.

Whether in a flipped or a traditional classroom, the author of this article has been extensively giving conceptual questions for homework and on exams, with each weekly homework assignment being composed of several (often one a day) "physical" nontrivial (rather complex, requiring "electromagnetic thinking") concept-based computational problems [21] and usually twice as many related conceptual questions [20]. Additionally, each midterm and final exam includes both computational problems and conceptual questions. Generally, students really like conceptual questions and appreciate the immediate learning benefits that they provide. In addition, this instructor has

Conceptual Questions: Example 6

CONCEPTUAL QUESTION 10.81 Initial transient voltage at generator terminals of a line. Assume that a lossless transmission line of characteristic impedance $Z_0 = 50\ \Omega$ is driven by a voltage generator of step emf $\mathcal{E} = 5$ V applied at $t = 0$, as shown in Figure 10.21. At $t = 0^+$, the transient voltage at the beginning (at generator terminals) of the line, $v_g(t)$,

(A) equals 5 V.

(B) equals 3.33 V.

(C) equals 2.5 V.

(D) equals 2 V.

(E) depends on the length of the line.

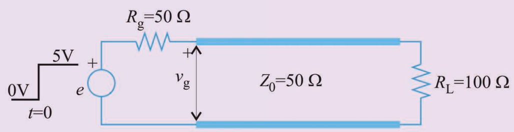


Figure 10.21 Circuit from Figure 10.8 but with a step excitation (step emf applied at $t = 0$); for Conceptual Question 10.81.

Common misconceptions: Confusing the transient response with the more familiar steady-state one. In steady state (e.g., time-harmonic regime), the generator voltage depends on the length of the transmission line.

Underlying concepts and equations:

In transient regime, prior to the return of any backward propagating wave reflected from the load, the generator sees, looking into the line, a purely resistive impedance equal to the characteristic impedance of the line, Z_0. Hence, the generator voltage is determined by the symmetric voltage divider, and equals 2.5 V.

FIGURE 5. Example 6 of a conceptual question in electromagnetics [20] dealing with the transient response of transmission lines, along with an outline of a common misconception and the underlying concepts and equations [21]. The correct answer is (C).

been giving MATLAB assignments requiring the students to write, test, and execute their own MATLAB programs as well as run existing codes [22] as optional assignments for extra course credit.

Generally, in assessments of student learning using conceptual questions, the performance of students and the effectiveness of instruction can be evaluated as the gain between the course pretest and posttest scores. Selected conceptual questions can readily be used by instructors as partial and final assessment instruments for individual topics at different points in the course and for the entire class.

For the purposes of ABET (or similar) accreditation compliances, conceptual questions can be easily implemented to precisely and directly assess students' understanding and mastery of individual principal course concepts (electromagnetic field and wave concepts). They can then be directly converted (mapped) to a quantitative assessment of individual course objectives (that every student passing the course should meet at a prescribed level). Course objectives are mapped to student outcomes, e.g., student outcomes (a)–(k) in ABET terminology, which are now being replaced by student outcomes (1)–(7) in the newest ABET language (applicable beginning in the 2019–2020 accreditation cycle) [36], for the entire program (e.g., electrical engineering program) and finally to the program educational objectives.

It is also possible to directly map conceptual questions to some of the student outcomes. Based on quantitatively assessed student performance on individual course concepts, the instructor can modify the instruction, delivery mode, assignments, tests, and even the course content. With this, conceptual questions become the main part of the assessment feedback mechanism (described, for instance, by the ABET Continuous Improvement criterion, which arguably is the most challenging one to achieve, document, and comply with).

Finally, note that an interesting discussion of the conceptual questions provided in [20] can be found in [43].

CONCLUSIONS

This article has introduced, framed, and discussed some possible uses of conceptual questions in teaching and learning electromagnetics. These questions can be applied to various modalities of active and collaborative teaching/learning, such as a flipped classroom and team discussions, and are ideally suited for different types of class or topic assessments to assess and motivate class prework, evaluate the achievement of class or course objectives, and appraise the improvement of student learning and competence for accreditation purposes.

Conceptual questions of this scope and intent are completely new in the electromagnetics area—and in practically all electrical and computer engineering areas. Also, this is one of the most complete and ambitious attempts to use them in science and engineering education overall. As future work, the conceptual questions platform shows the potential to be advanced into a modern multipurpose general tool and environment for instruction, learning, and assessment.

ACKNOWLEDGMENT

This work was supported in part by the National Science Foundation under grant EEC-1519438.

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MEETINGS & SYMPOSIA

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