Received: 17 June 2018 | Accepted: 9 September 2018
DOI: 10.1002/cae.22073

RESEARCH ARTICLE

WILEY

Computer-assisted learning of electromagnetics through MATLAB programming of electromagnetic fields in the creativity thread of an integrated approach to electrical engineering education

Branislav M. Notaroš | **Ryan McCullough** | **Sanja B. Manić** | **Anthony A. Maciejewski**

Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, Colorado

Correspondence
Branislav M. Notaroš, Department of Electrical and Computer Engineering, Colorado State University, 1373 Campus Delivery, Fort Collins, CO 80523.
Email: notaros@colostate.edu

Funding information
National Science Foundation, Directorate of Engineering, Division of Engineering Education and Centers, Grant number: EEC-1519438

Abstract

This paper discusses an integrated approach to electrical-engineering education that incorporates computer-assisted MATLAB-based instruction and learning into the junior-level electromagnetics course and newly created learning studio modules (LSMs). In this model, creativity class sessions are followed by two comprehensive and rather challenging multi-week homework assignments of MATLAB problems and projects in electromagnetic fields. This is enabled by a unique and extremely comprehensive collection of MATLAB computer exercises and projects, reinforcing all important theoretical concepts, methodologies, and problem-solving techniques in electromagnetic fields and waves, developed by one of the faculty team members. These tutorials, exercises, and codes constitute a modern tool for learning electromagnetics via computer-mediated exploration and inquiry, exploiting the technological and pedagogical power of MATLAB software as a general learning technology. The novel approach introduces students to MATLAB programming of electromagnetic fields, as opposed to just passive demonstrations of MATLAB's tools and capabilities for computation and visualization of fields. MATLAB programming tutorials and assignments are designed to deepen student engagement and accommodate different learning styles so students can learn more effectively. In addition to improving students' understanding and command of MATLAB use and programming within the electromagnetics context and beyond, these exercises increase their motivation to learn and appreciation of the practical relevance of the material, and equip them with the tools and skills to excel in other courses and projects. The results of this project were qualitatively analyzed through feedback surveys given to the students at the end of each MATLAB assignment. The Electromagnetics Concept Inventory was also used.

KEYWORDS

computers and education, computer-assisted instruction and learning, computer exploration in electromagnetics, electromagnetics teaching and learning, MATLAB-based instruction and learning, MATLAB tutorials, exercises, and codes

 © 2018 Wiley Periodicals, Inc.

1 | INTRODUCTION

1.1 | Overview of pedagogical approach

Supported by a 5 year REvolutionizing engineering and computer science Departments (RED) grant from the National Science Foundation (NSF), a diverse team of educators at Colorado State University (CSU) are implementing a new approach to teaching and learning that reimagines the roles of the faculty and moves away from the traditional course-centric structure [5]. As described in the *IEEE Access* article "A Holistic Approach to Transforming Undergraduate Electrical Engineering Education" [25], our pedagogical model builds on the concept of "nanocourses" to facilitate knowledge integration (KI), a learning model grounded in education pedagogy and supported by research. The approach blurs the lines between courses because the faculty take a systems view of the curriculum to identify the fundamental technical concepts of an electrical and computer engineering (ECE) education, independent of courses. These concepts are then rearranged and organized into cohesive learning studio modules (LSMs) to lay the groundwork for real-world applications. Each LSM is self-contained and addresses one anchoring concept and a set of sub-topics in a given core competency area [5,25]. Although a departure from the traditional course structure, LSMs still provide a path for students to learn all the intended topics in a rigorous fashion.

Aiming to connect abstract concepts to the real world of engineering, KI activities are then created to put learning in context and illustrate the societal relevance of engineering knowledge [5,25]. Serving as a mechanism for helping students grasp the commonality and correlations between core concepts across the curriculum, KI activities show students how LSM fundamentals are integrated to form the building blocks of a complex piece of ubiquitous technology.

1.2 | Creativity in the technical core of the curriculum

While our 5-year RED project spans the entire undergraduate program, special attention is given to the technical core, or junior year, of the ECE curriculum. In addition to instilling deep technical knowledge of the discipline, faculty are working in partnership to interweave the following threads throughout the curriculum to help students develop skills that will allow them to thrive as engineers [25]:

1. Creativity thread—integrates research, design, and optimization.
2. Foundations thread—illustrates why math matters in the world of engineering.
3. Professional formation thread—emphasizes professional skills deemed important by industry.

This paper dives into the creativity thread of the project, sharing details about how the department is using learning technology tools, in this case MATLAB, to enrich and assess learning.

1.3 | Challenges of electromagnetics instruction and learning

For the RED project, technical core material encompasses signals and systems, electromagnetics, and electronics. This paper focuses on the role and importance of electromagnetics in the undergraduate curriculum, and the challenges of its instruction and learning. It has been noted by several researchers [2,6,19,41] that students have an opinion that introductory electromagnetics is a difficult subject, and instructors also find it a difficult subject to teach. Indeed, while electromagnetic theory or theory of electromagnetic fields and waves is a fundamental underpinning of technical education, it is often perceived as the most challenging and demanding course in the electrical engineering (EE) curriculum. The material is extremely abstract and mathematically rigorous, and students find it difficult to grasp, which is not unique to any particular school/department, country, or geographical region.

Researchers attribute the difficulty to three main factors: (i) the use of vector mathematics, which some students can view as rather abstract; (ii) introductory classes frequently only cover very idealized situations that do not have true physical applications; and (iii) realistic electromagnetics examples in a laboratory setting are difficult to create. These three issues create various problems derived from commonly researched factors in engineering student attrition and achievement. Dinov et al. [9] also point out that classes that rely heavily on mathematics tend to miss other learning modalities such as visual and active learning. If the difficulty related to visual and active learning is not addressed, it becomes an issue with the instructor/student learning styles mismatch, as has been reported in multiple studies [3,12–14,24]. In addition, if the realistic examples and true physical applications are not presented in a way that is both rigorous and relevant, students tend to lose motivation [15].

1.4 | Understanding student learning styles

Learning styles are characteristic preferences for alternative ways of taking in, and processing, information. The theory of learning styles has been studied for decades, beginning with Kolb's learning styles model in 1984. There are different variations on learning styles, but Felder and Silverman's index of learning styles (ILS) [13] is commonly used in engineering education. They categorize five pairs of complementary learning styles: sensing and intuitive; visual and auditory;

inductive and deductive; active and reflective; and sequential and global.

1. *Sensing and Intuitive*: Sensing learners deal with the outside world through observing and gathering data through the senses, while intuitive learners indirectly perceive information through speculation and imagination.
2. *Visual and Auditory*: Visual learners use sights, pictures, and diagrams, whereas auditory learners prefer sounds and text.
3. *Inductive and Deductive*: Inductive learners prefer a reasoning progression from observations, measurements, data, etc., to generalities, that is, governing rules, laws, and theories. Deductive learners prefer the opposite progression of inductive learning, going from the governing ideas to explaining new observations.
4. *Active and Reflective*: Active learning takes place when experimentation involves discussions, explanations, or testing in the outside world. Reflective learners, meanwhile, prefer to go through these processes more introspectively. Kinesthetic learning is another commonly acknowledged modality of learning, where learners prefer exploring through touching and interacting, but Felder and Silverman consider this to be part of the active learning style.
5. *Sequential and Global*: Sequential learners prefer the standard layout of class content where the concepts are introduced and learned systematically. Conversely, global learners prefer to learn in fits and starts, needing to see how all the pieces fit together before they can make sense of any small part.

1.5 | Importance of adapting instructional methods to motivate learners

Although there is some debate on the effectiveness of matching instructional methods to a student's assessed learning style, there have been significant studies showing that a mismatch in learning styles leads to decreased performance and a higher attrition rate [3,12–14,24]. In Seymour and Hewitt's study "Talking about Leaving" [39], the data showed that grade distributions of students who leave technical curricula are essentially the same as the distributions of those who continue. Their findings revealed that some of the higher performing students leave because of dissatisfaction with their instruction. This fact was also recorded by Bernold et al. [3] in their three-year, 1,000+—student study, where they systematically tested the learning style preferences and behaviors of the students and tracked their successes, failures, and paths throughout 3 years of the engineering program. They found that students who had the greatest mismatch in learning style preference versus the standard teaching style preference (lectures) had the largest attrition rate and the poorest grade point average (GPA), even when the comparison was done through a Scholastic Assessment Test (SAT) mathematics covariation. However, as Litzinger et al. [24] note, students with any learning style preference have the potential to succeed at any endeavor. Learning styles and modalities are simply preferences that dictate the ways in which people feel the most comfortable learning. Felder and Brent [12] note that how much a student learns in a class is governed in part by that student's native ability and prior preparation but also by the compatibility of the student's attributes as a learner and the instructor's teaching style.

A large part of student performance is tied to their motivation. College students, like all adults, have an issue motivating themselves to study material if it is not applicable to their lives or their future professions [31,42]. Ulaby and Hauck [41] observed that students learning in the standard lecture-style environment tend to doubt the usefulness of learning the subject of electromagnetics as they cannot see how it can be applied directly to other parts of the curriculum and how it will benefit them once they graduate. The cognitive science based study "How People Learn" [31] recommends a model to mitigate this issue, which calls for instructional activities to focus on the most important principles and methods of a subject while building on the learner's current knowledge and conceptions. The activity should also utilize techniques known to promote skill development, conceptual understanding, and metacognitive awareness rather than simple factual recall.

1.6 | Background on computer-assisted learning and programming in technical education

Computer software has been used to aid student learning in electromagnetics for quite some time [1,4,7,8,11,16,17,20–23,26,32–38,40]; although this use has expanded in recent years, it is not widespread yet and is not universally implemented. As Mias [26] notes, computer-assisted learning significantly improves the teaching of electromagnetics. He goes on to discuss some of the currently utilized methods of incorporating computer-assisted learning including: educational graphical interfaces for electromagnetic field visualization, the use of spreadsheet programs in solving electromagnetic problems, the use of university and/or industry-developed computational electromagnetics software to solve real life problems and gain an insight on electromagnetic field phenomena, and virtual laboratories. These solutions, although they can be shown to improve teaching, lack one specific task: programming. Mias [26] and Read [35] discuss the advantages of utilizing programming in electromagnetics instruction. They both note that the benefit

of writing computer code is that it increases the students' need to understand fundamental field concepts of the problem involved and the need to be able to obtain the conventional analytical solutions of simple problems. Programming, as well as the other methods of computer-assisted learning, also brings in the possibility for design work, a core aspect of the creativity thread within the RED project, in a way that was not possible through traditional methods.

As another example of the effectiveness of computer-assisted learning in engineering/science education, generally, we look to the work by Dinov et al. [9]. In instructing several statistics courses of various levels, these authors experimented with a statistics online library provided by the NSF called statistics online computational resource (SOCR). While integrating this resource into their classrooms and post-work did not result in statistically significant gains in comparison to the traditional classroom, they did receive much more positive feedback for the course through a qualitative survey, and the retention rate of the supplemented classes was significantly higher. This shows that even if students do not learn more through programming, which is contrary to what Mias and Read suggest, they still enjoy the content matter more and are more willing to stick with the class.

The use of programming in the current EE curriculum generally follows the same trend in that students are frequently only required to take a single programming course at the beginning of their program. These courses, which are generally offered through the university's Computer Science (CS) department, teach students topics more related to CS, such as sorting and searching, rather than topics that are better suited to EE, such as matrix manipulation [19]. The students are then expected to use these rudimentary, unrelated programming skills to later program concepts such as vector algebra and calculus, multivariable functions, three-dimensional (3-D) spatial visualization, numerical integration, optimization, and finite-difference and finite-element methods. This can be a struggle for many students without a stronger background in matrix manipulation and calculus-related programming.

1.7 | Utilizing MATLAB to deepen learning and inspire creativity

To adapt our instructional methods to motivate students, and address the learning considerations outlined previously, we have chosen MATLAB® (by MathWorks, Inc., Natick, MA) as the learning technology and modeling software language for the creativity thread of the RED project. Evidence shows that students find MATLAB easy to use [35], and it is considered an important tool that ECE students and future engineers need to use effectively. By having a single software platform that is consistently used throughout the curriculum, students gain proficiency with the programming environment, allowing them to shift their focus from learning programming to understanding the technical content of what they are programming.

This paper presents inclusion of computer-assisted MATLAB-based instruction and learning in the electromagnetics course and LSMs of the RED project, where the students are implementing the core LSM concepts they learned into a "virtual electromagnetics testbed" using MATLAB, as part of the creativity thread. The students are taught "hands-on" electromagnetics through MATLAB-based electromagnetics tutorials and assignments of exercises and projects in MATLAB. To enable this, the lead author of this paper has developed a unique and comprehensive collection of approximately 400 MATLAB computer exercises, problems, and projects, covering and reinforcing practically all important theoretical concepts, methodologies, and problem-solving techniques in electromagnetic fields and waves [29], as a modern tool for learning electromagnetics via computer-mediated exploration and inquiry. These tutorials, exercises, and codes are designed to maximally exploit the technological and pedagogical power of MATLAB software as a general learning technology. Similar to the study done by Dinov et al. [9], the results of this work are qualitatively analyzed through a survey given to the students that recorded their feedback about the integration of MATLAB in their coursework. A preliminary report on this work appears in a conference proceedings [30].

When MATLAB has previously been chosen as a platform for computer-assisted learning [1,4,7,8,11,16,26,32,37,38], the instructors frequently have created a graphical user interface (GUI) or some similar interface that the students interact with as opposed to writing their own programs. As discussed above, programming forces students to think about the problem logically and to pay attention to the details, while still having a big picture of the problem at hand. Simply letting a GUI do the calculations and imaging the results is not as conducive to the learning process as the active process of programming electromagnetics.

Note that the "creativity" term within this study should be considered and appreciated in a broad sense. The "creativity thread" of our RED project is an umbrella for a variety of research, analysis, and design related activities that students perform individually and in teams within the individual courses and through projects at different stages in the curriculum. Through this thread, we are attempting to inspire and enhance not only students' creativity but also a number of other related, abilities and skills essential for their preparation for the real world of engineering. Likewise, the link between the "creativity" and the inclusion of computer-assisted MATLAB-based instruction and learning in the ECE electromagnetics course and LSMs as presented and discussed in this work should be understood broadly, in

multiple ways. Foremost, the "creativity" term linked to the use of MATLAB in electromagnetics classes here comes from the context of this presented implementation, namely, as part of the creativity thread of the RED project, and practically all references to "creativity" in this paper are within this context. In addition, MATLAB exercises can help the students develop a stronger intuition and a deeper understanding of electromagnetic field theory, examples, and problems, which 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 analytical, evaluative, and creative thinking about and dealing with electromagnetic fields by exploring various "what ifs" and bridging the fundamental aspects and applications without being overwhelmed with abstract and often overly complicated and dry mathematics of analytical solutions. Furthermore, most programming tasks in support of scientific and engineering computing are, arguably, creative to some extent, and so is the proposed MATLAB programming of electromagnetics performed by students, as opposed to a passive computer demonstration. Finally, our MATLAB problems are designed and assigned to help the students develop and enhance their MATLAB skills irrespective of the electromagnetics context, which can then be utilized in other courses in the curriculum, as well as in research activities and projects, and there even more closely and directly tied with the innovation and creativity—for example, within design work.

1.8 | Novelty and broader impacts of proposed MATLAB programming of electromagnetics in the creativity thread

Overall, the principal novelty of our approach is the introduction of MATLAB programming of electromagnetics performed by students, as opposed to passive instructional methods. Our approach has a twofold goal for students as learners: (i) gaining and solidifying their knowledge of fundamentals of electromagnetic fields and (ii) building and enhancing their understanding and command of MATLAB syntax, functionality, and programming in the framework of electromagnetics. Our approach attempts to capitalize on a win-win combination of the pedagogical benefits of MATLAB-based electromagnetics education and students' computer-related skills and interests.

Another benefit of our approach is that it enhances students' MATLAB skills, which are used throughout the creativity thread of our integrated approach to ECE education, as well as in KI activities that span multiple courses across the curriculum. In addition, some of the most important pedagogical features of MATLAB related to the instruction and comprehension of electromagnetic fields and other ECE topics are its abilities to manipulate and visualize vectors and spatially distributed physical quantities, numerically solve problems, and use symbolic programming to reinforce analytical solutions.

This paper shares examples of the MATLAB assignments we delivered as part of the creativity thread. We also demonstrate how these assignments engage a broad range of learning styles, to include those students who do not thrive in a lecture style learning environment, such as visual, active, global, and inductive learners. We also illustrate how our approach increases students' motivation to learn, their attitudes toward the subject, and appreciation of the practical relevance of the material. Finally, our paper outlines how our work helps the students develop and improve the understanding and command of MATLAB use and programming, within and beyond the electromagnetics context.

2 | METHODS AND IMPLEMENTATION

2.1 | Introducing MATLAB programming of electromagnetic fields in an electromagnetics course

MATLAB-based instruction and learning was introduced in ECE 341, the Electromagnetic Fields I course in the ECE Department at CSU during the fall semester of 2016. This is the first course of a mandatory sequence of two electromagnetics courses covering static and low-frequency (quasi-static) electric, magnetic, and electromagnetic fields (commonly referred to as a classical fields course) with the second course in the sequence dealing with generation and propagation of unbounded and guided electromagnetic waves and transmission lines, namely, a waves course. The fields course was integrated, through the RED project, with signals/systems and electronics courses running in the same semester. The five LSMs of the course are: LSM1 Electrostatic Field in Free Space; LSM2 Electrostatic Field in Material Media; LSM3 Steady Electric Currents; LSM4 Magnetostatic Field; and LSM5 Low-Frequency Electromagnetic Field.

In creativity class sessions, students were given MATLAB tutorials/lectures, with ample discussions of approaches, programming strategies, MATLAB formalities, and alternatives. These were followed by comprehensive and rather challenging multi-week homework assignments consisting of MATLAB problems and projects in electromagnetic fields. In addition to the creativity class lectures, each MATLAB assignment included a number of tutorial exercises with detailed solutions combined with listings of MATLAB code. Even these exercises were assigned and graded, as their completion required creation of MATLAB programs from the provided portions of code, actual execution of the program, and generation and presentation of the results. Normally, all

new concepts, approaches, and techniques in MATLAB programming as applied to electromagnetic fields were covered in tutorials, to provide students with additional guidance for completing similar exercises on their own.

Some specific technical and pedagogical features of these MATLAB exercises, projects, and codes include vector field computation, visualization of spatially distributed scalar and vector quantities, symbolic and numerical programming, for example, symbolic and numerical integration, and solutions to nonlinear problems. There are many other features that may be suitable and implementable into a fields class [29], that were beyond our particular implementation in this study and will be part of our future work. Another large set of features would apply to the waves course or the waves portion of the electromagnetics course in a single-course scenario [29].

The MATLAB exercises and projects for the electromagnetic fields course were created and chosen by the instructor of the course to best support the electromagnetics LSMs and the RED project as a whole [29]. The instructor also authored the textbook used for the course [28], and, as such, was able to choose MATLAB exercises that fluently supported the traditional course content. As a part of the assignments, the students were expected to take the core LSM concepts they learned in class and implement and explore them in the form of computer exercises utilizing MATLAB.

Essentially, the students are learning MATLAB in the context of electromagnetics and learning electromagnetics in the context of MATLAB. Moreover, in our opinion and experience, including programming actively challenges and involves the student, providing additional, prolonged benefits of learning as compared to a passive computer demonstration. This is consistent with the observations described by both Hoole [19] and Hoburg [18]: The mere use of computers does not enhance learning skills; it is when students develop their own programs or general purpose software that their curiosity and creativity is aroused and they learn the most.

The observations described by Hoole and Hoburg above also fit well with the educational theory of learning styles, discussed in section 1. Although simply using computers to model a system can help the visual learners to see a visual representation of the electric and magnetic fields, it does not help active learners engage with the material. Also, because students do not have to consider the fundamental field concepts to simply use a computer, the students do not gain a full understanding of the origins behind the fields, a key aspect of electromagnetism. By presenting the overlying phenomena as a question/problem and using a programming approach to modeling fields and forces, students are required to build the solution from a set of underlying concepts, an aspect of inductive learning. This quality is a key factor in understanding material. As Felder and Silverman [13] state in their paper "Learning and Teaching Styles in Engineering Education," the benefits claimed for inductive learning include increased academic achievement, enhanced reasoning skills, longer retention of information, improved ability to apply principles, and increased capability for inventive thought. The learning style advantages of programming versus normal simulation software do not end there. The ability to manipulate the program and explore various "what ifs" and applications while still considering the fundamental aspects at play are a key component of learning electromagnetism through a global perspective. Therefore, through using programming to model electric and magnetic fields in given situations, the learning styles less frequently reached by typical lecture style teaching and standard simulation software (active, global, and inductive) are all achieved through our approach.

As explained in section 1, learning styles were not our only consideration when designing and choosing the MATLAB exercises/problems; we also considered the relevance of the problems in terms of actual engineering design and their relationship to current material covered in other courses. Some of the problems simply cannot be related to the students' everyday lives and engineering designs because many of the basic concepts are not strictly applied; however, when there was an application, we tried to include it. For example, one problem required the students to use a GUI calculator that calculates the capacitance of a microstrip line and other common transmission lines and capacitor structures. Some of the more abstract relationships were also addressed in the creativity section. For instance, as most of the programming dealt with the visualization of electric and magnetic fields and forces, the ideas of electromagnetic interference (EMI) were addressed and discussed to stress the importance of knowing the field structures and forms to be able to predict where EMI and various types of capacitive, conductive, inductive, radiative, etc., couplings could be an issue.

By writing and executing their own MATLAB programs to solve problems and generate results presented in figures, diagrams, movies, and animations, students gain a stronger intuition and deeper understanding of electromagnetic fields, one of the most difficult subjects in EE, primarily because it is extremely abstract. Simultaneously, these diverse MATLAB projects and exercises help students to gain comprehensive operational proficiency in concepts and techniques of MATLAB use and programming. This knowledge and skill can then be applied effectively in other areas of study, including other courses in the curriculum, most notably in the signals/systems and electronics courses in the junior year, which is the focus of the RED project.

In addition, as Hoole [19] suggests, computer modeling and programming in the context of engineering education allows the students to not only gain an understanding of content, but to confront and appreciate the reality that design is an iterative modeling and analysis process. To help students address and recognize this process and its benefits, some

MATLAB exercises/problems required students to create programs to solve problems that they already had to solve "by hand" for homework or that were done "conventionally" in class. Some other problems asked the students to implement the fundamental concepts and equations from the course in MATLAB programs, carry out calculations and visualizations using their programs, and draw and report relevant conclusions and results. Another class of problems directly addressed real-world practical applications of electric and magnetic fields discussed in the course. All problems were designed and assigned to help the students develop and enhance their MATLAB skills, irrespective of the electromagnetics context.

2.2 | Illustrative examples from creativity thread MATLAB assignments in electromagnetics classes

Example Problems 1 and 2—given in Table 1 and Figures 1 and 2—show how some of the MATLAB problems encourage students to think about how small changes to the MATLAB program can lead to vastly different results. The results from these examples also show the power of MATLAB to visualize vectors, vector algebra, and 3-D spatially distributed quantities. As mentioned above, this clearly addresses the visual learning style that is normally ignored in a traditional lecture. In terms of MATLAB programming skill development, Problem 1, for example, teaches the students to perform vector numerical integration, and to visualize vector fields by means of arrows in 2-D space using the MATLAB function "quiver," having previously defining a 2-D mesh of field points using the MATLAB function "meshgrid." None of these MATLAB tasks are simple and all have many different applications.

Moreover, in Example Problem 1, vector integration is carried out based on spatial subdivision of the integration domain, approximation of charges on integration segments as equivalent point charges, and computation of the Cartesian vector components of the total electric field at each node of the field mesh as a sum of all elemental field components—in MATLAB. This exactly coincides with the analytical procedure and thought flow taught in regular class sessions for obtaining the fields due to given continuous charge distributions by vector summation of the fields contributed by the numerous equivalent point charges making up the charge distribution. So students are now "instructing" a computer to evaluate the electric field due to a spatial charge distribution by vector integration in a computer program in essentially the same way as they were instructed to do so analytically in fields classes. There perhaps is no better way for students to acquire and embrace the principle of superposition, which is a consequence of the linearity of the electromagnetic system in this and most other cases and is one of

TABLE 1 Example Problems 1–4 from the creativity thread MATLAB assignments in the electromagnetics (fields) class

Problem #	MATLAB problem statement
1	MATLAB function "quiver" is used for visualization of field vectors in 2-D space. Input data are coordinates of nodes in a mesh in a Cartesian coordinate system and intensities of field components at the nodes. Implement "quiver" to visualize the electric field distribution due to a uniform straight line charge of finite length l and total charge Q placed along the x-axis in free space. Although the analytical solution is available in this case, given by [28] $E = \frac{Q}{4\pi\varepsilon_0 \mathrm{ld}}[(\cos\theta_2 - \cos\theta_1)\widehat{x} + (\sin\theta_2 - \sin\theta_1)\widehat{y}]$ for the situation shown in Figure 1, the electric field vector at each node of the mesh should be computed by vector numerical integration of elementary fields due to equivalent point charges along the line representing short segments into which the line is subdivided. With such an integration (superposition) procedure, this MATLAB program may be applicable, with appropriate modifications, to many similar and more complex charge distributions, where the analytical expression for electric field components is not available or is difficult to find. Output from the MATLAB code is shown in Figure 2.
2	Repeat the previous MATLAB Exercise but for three equal point charges Q residing at vertices of an equilateral triangle of side a in free space.
3	Write a program in MATLAB that uses previously created programs and calculates and plots the electric force on a point charge due to N other point charges in free space. The input to the program consists of N, coordinates of charge points, and charges Q_1, $Q_2, \ldots, Q_N$, as well as coordinates and charge of the point charge on which the force is evaluated. Then use this code to plot the force on one of three equal point charges at vertices of an arbitrary triangle. Figure 3 shows an output from the MATLAB code.
4	Write a MATLAB program that displays the distribution of the electricpotential due to an electric dipole (Figure 4) with a moment $\mathbf{p} = Qd\hat{z}$ located at the origin of a spherical coordinate system. As output, the program provides two plots in the plane defined by $y = 0$ in the associated Cartesian coordinate system: one representing the potential by means of MATLAB function "pcolor" (that uses color to visualize the third dimension) and the other showing equipotential lines with the help of MATLAB function "contour." Depicted in Figure 5 is an output from the MATLAB code.

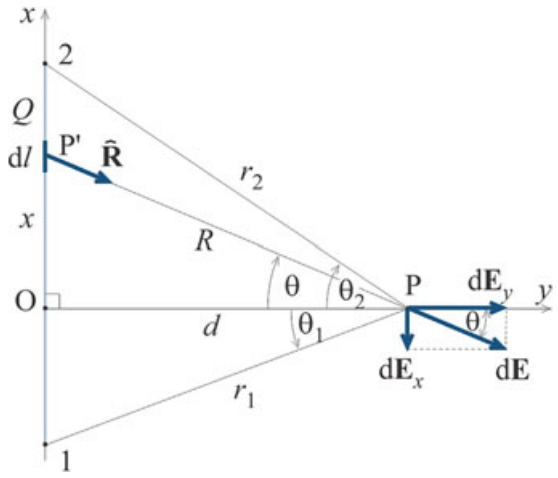

FIGURE 1 Geometry for Example Problem 1 (from MATLAB assignment 1) in Table 1 [28]

the most important principles in electromagnetic (and ECE in general) analysis, computation, and design, than to "teach" the computer how to do it based on fields analytics from classes. This is key in developing students' problem-solving (analytical and computational) skills for true 2- and 3-D vector problems, and essentially any complex problem. While there is no universally optimal algorithm for solving complex problems, it is wise to use superposition whenever possible—that is, to break up a complex problem into simpler ones, and then add up (integrate) their solutions to get the solution to the original problem [28]. These fundamental concepts of linearity and superposition are reinforced across multiple ECE subjects, especially in the signals/systems and electronics courses within the RED KI activities.

Example Problem 3, presented in Table 1 and Figure 3, also shows an example of a vector visualization question/problem and MATLAB programming task given to the

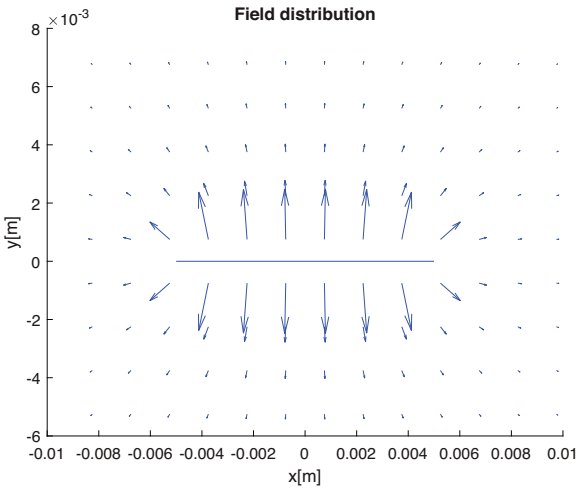

FIGURE 2 Graphical output from the MATLAB code for Example Problem 1 in Table 1, for the following input: Line length (Figure 1) in cm: 1; Total charge in nC: 1

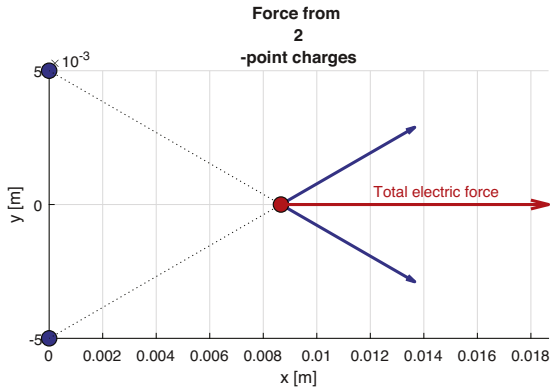

FIGURE 3 Graphical output from the MATLAB code for Example Problem 3 (from MATLAB assignment 1) in Table 1, for an adopted position of charges

students, but now extends the visualization from 2- to 3-D space by using the MATLAB function "'quiver3." In addition, this problem helps students to recognize and appreciate the vector electric forces, both the components and the resultant, due to point electric charges. The resultant force on a charge is computed again using the principle of superposition, as the vector sum of partial forces due to other charges in the system. Although this and similar problems are only ideal and do not have immediate counterparts in reality, they are still useful as the students have to consider the fundamental concepts to program the system, and the end result helps them to visualize field effects, a vital capability when addressing some real-life engineering problems.

Example Problem 4 (Table 1 and Figures 4 and 5) helps students visualize spatial patterns and changes in a scalar variable using the MATLAB functions "pcolor" (with color continuously representing the function value as the third dimension above a 2-D cut of 3-D space) and "contour" (with colored lines representing cuts in a plane of surfaces having the same value of a 3-D spatially dependent quantity at all points—equipotential, $V = \text{const}$, surfaces in this case). It also develops and solidifies the comprehension and mastery of an important concept of an electric dipole (Figure 4) and the electric potential (and consequently the electric field vector) that it produces in 3-D space.

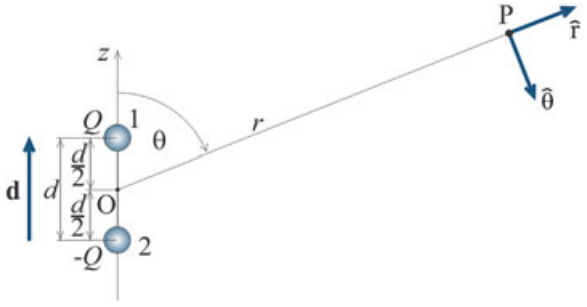

FIGURE 4 Geometry for Example Problem 4 (from MATLAB assignment 1) in Table 1 [28]

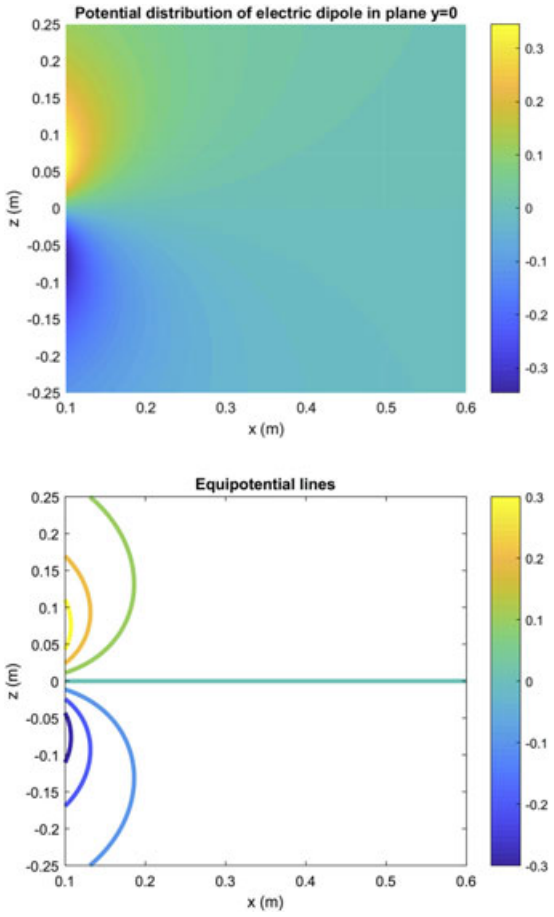

FIGURE 5 Graphical output from the MATLAB code for Example Problem 4 (from MATLAB assignment 1) in Table 1 (Figure 4), using MATLAB functions "pcolor" (top panel) and "contour" (bottom panel)

Examples of MATLAB problems that require the students to compare a MATLAB solution to the "by hand" solution are included as Example Problems 5 and 6, given in Table 2 and Figures 6–8. Generally, students are often specifically asked to redo some of the conventional computational problems they had for homework (typically, Problems from the book [28]) or that were done in class (typically, Examples from the book [28]), namely, either the same or similar problems, now using MATLAB to experience firsthand the power and utility of numerical and symbolic analysis and computation. Solving the problems and studying the topics both analytically and using MATLAB is extremely beneficial, as it significantly reinforces the fundamental concepts required for both approaches and ensures students are addressing the active, global, and inductive learning styles. Note that Example Problems 5 and 6, given in the Creativity Thread MATLAB assignments in the fields class, as well as the Related Classical Problems in Table 2, done in class or for homework, are all "physical," realistic, practical, interesting, nontrivial problems, and not purely formulaic (plug-and-chug) or purely "mathematical," dry, formal problems. They are very challenging to address, analyze, and solve both analytically and in MATLAB, and thus very beneficial for students' learning in both contexts. In addition, students are challenged to implement decision making and equation setting/solving processes that they are carrying out analytically when solving problems classically into a general algorithm and software so the computer can provide the result for any set of input values, and not just for the ones specified in a particular problem.

Figures 9–12 present additional example results from the MATLAB assignments illustrating the power of MATLAB computation and visualization in electromagnetics (fields). Namely, Figure 9 shows the results of a question/problem that required students to address the important concept of boundary conditions for a dielectric-dielectric boundary. The programming aspect enforces the fundamental concepts, utilizing a detailed tutorial for a similar, preceding, MATLAB problem, while the result encourages a visual learning perspective.

Figure 10 depicts an example where the programming was actually done for the students to create a GUI. This GUI, however, is very useful as it helps the students to understand and utilize the capacitance "produced" by different capacitors and transmission line geometries. This addresses the students' need for problems relevant in their own lives. In addition, interested students were able to explore and play with the MATLAB script (source code) for the GUI and learn firsthand, or at least get a rough idea, how such real-life complex GUIs are designed, developed, and coded in MATLAB.

Figure 11 portrays an example problem that also addresses a main concept in electromagnetism while having a very specialized application to real life in areas like particle accelerators. The programming behind the result will once again force students to fully consider the fundamental concepts and any special issues due to the logic requirements of a computer.

Finally, Figure 12 addresses the common visualization issue when time-harmonic alternating current exists in a straight-wire conductor, and, even more difficult, the visualization of the nearby electric field it produces. Because these concepts are hard to grasp and visualize, the results show them together, through two different but coupled graphical means: a plot showing the variation of the current over time in a given cross-section of the wire and a 2-D vector representation, as it varies in both time and space, of the electric field intensity vector around the wire induced (generated) by the current, with the two graphical representations being viewed simultaneously in a movie.

3 | RESULTS AND DISCUSSION

Due to many changes associated with the RED project in the junior year of the EE program at CSU in the Fall of 2016, we decided that there would be simply too much work for the students if they had additional MATLAB homework project

TABLE 2 Example Problems 5 and 6 from the creativity thread MATLAB assignments in the electromagnetics (fields) class

Problem #	MATLAB problem statement	Related classical problem
5	This MATLAB exercise analyzes breakdown in a spherical capacitor with a multilayer dielectric. Consider a spherical capacitor with N concentric dielectric layers. The inner radius, relative permittivity, and the dielectric strength of the ith layer are a_i, ε_{ri}, and E_{cri}, respectively ($i = 1, 2, \ldots, N$). The inner radius of the outer conductor of the capacitor is b. Write a MATLAB program to find which dielectric layer would break down first after a voltage of critical value is applied across the capacitor electrodes and to compute the breakdown voltage of the capacitor. Test the program for $N = 3$, $a_1 = 2.5$ cm, $a_2 = 5$ cm, $a_3 = 7$ cm, and $b = 9$ cm, if the dielectrics constituting layers 1, 2, and 3 are polystyrene, quartz, and silicon, respectively (use GUIs from MATLAB Exercises I.16 and I.17 to get the values of material parameters). HINT:The data input is realized as in MATLAB Exercise I.3. We implement a generalization of Eqs. (2.241) and (2.242) from the book [28] to the case of an arbitrary number (N) of layers, and, instead of only two charges and, we now have an array of such charges. For finding the minimum charge in the array, we use MATLAB function "min," which also returns as output the position (index) of the minimum value in the array. Then the corresponding breakdown voltage is computed based on Eqs. (2.240) and (2.241) from the book [28].	(Book [28] Example 2.32) The dielectric of a spherical capacitor consists of two concentric layers, as shown in Figure 6. The relative permittivity of the inner layer is $\varepsilon_{r1} = 2.5$ and its dielectric strength $E_{cr1} = 50$ MV/m. For the outer layer, $\varepsilon_{r2} = 5$ and $E_{cr2} = 30$ MV/m. Electrode radii are $a = 3$ cm and $c = 8$ cm, and the radius of the boundary surface between the layers is $b = 5$ cm. Calculate the breakdown voltage of the capacitor. (Book [28] Problem 2.75) Consider the spherical capacitor with two concentric dielectric layers in Figure 6 and assume that the inner dielectric layer is made from mica ($\varepsilon_{r1} = 5.4$), whereas the outer layer is oil ($\varepsilon_{r2} = 2.3$). The geometrical parameters are $a = 2$ cm, $b = 8$ cm, and $c = 16$ cm. The dielectric strengths for mica and oil are $E_{cr1} = 200$ MV/m and $E_{cr2} = 15$ MV/m, respectively. The oil is then drained from the capacitor. Find the breakdown voltage of the capacitor in (a) the first state (outer layer is oil) and (b) the second state (outer layer is air).
6	Consider a simple nonlinear magnetic circuit with an air gap, shown in Figure 7, and redo Example 5.13 from the book [28] but now in MATLAB. Write a MATLAB code that plots the magnetization curve of the ferromagnetic core and the load line of the circuit (in the same graph), and computes numerically and plots the operating point of the circuit. Compare the result to the analytical solution in Example 5.13. HINT: Use function "magCurveSolution" (from MATLAB Exercise II.15) and see the tutorials to MATLAB Exercises II.17 and II.4. Figure 8 shows the graphical presentation of the MATLAB solution.	(Book [28] Example 5.13; also book [28] Problem 5.21) Consider a magnetic circuit consisting of a thin toroidal ferromagnetic core with a coil and an air gap shown in Figure 7a. The coil has $N = 1{,}000$ turns of wire with the total resistance $R = 50\ \Omega$. The length of the ferromagnetic portion of the circuit is $l = 1$ m, the thickness (width) of the gap is $l_0 = 4 =$ mm, the cross-sectional area of the toroid is $S = S_0 = 5\ \text{cm}^2$, and the emf of the generator in the coil circuit is $E = 200$ V. The idealized initial magnetization curve of the material is given in Figure 7b. Find the magnetic field intensities in the core and in the air gap.

assignments every week or every other week on top of everything else required of them due to these changes. As such, the electromagnetics (fields) instructor only gave two separate large multi-week MATLAB assignments that were optional for extra course credit. Consequently, a quantitative analysis of how these assignments affected the students' grades is not appropriate. Instead, at the end of each MATLAB assignment, the students were given a survey to complete, which measured their thoughts, opinions, reactions, and feelings about how the assignment affected their understanding and enjoyment of both electromagnetics (fields) and MATLAB itself.

In particular, the students who chose to complete the MATLAB assignments were asked to complete a survey regarding their perceptions on the use of MATLAB and its integration into the curriculum. The surveys were voluntary and anonymous and the students were told that we would look at the results of the surveys only in aggregate form. The survey questions shown below were created by the course instructor. The students responded using an unbalance odd Likert scale. The following values were used:

1. Yes, a lot (3).
2. Yes, somewhat (2).
3. Not at all (0).
4. No opinion (Not Counted).

The first survey had a response/participation rate of 46% (39 out of 85 students in class), while the second survey only had a response rate of 22% (19 out of 85 students). Table 3

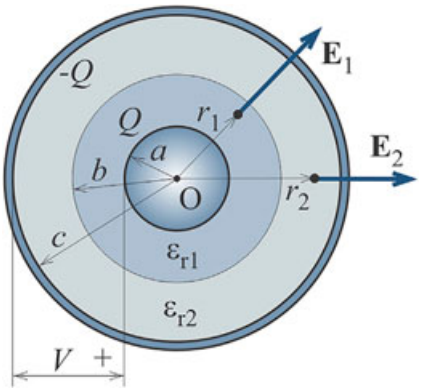

FIGURE 6 Geometry and material properties for Example Problem 5 (from MATLAB assignment 2) in Table 2 [28]

shows the results of the surveys with the average response (AR) and coefficient of variation (CV) presented. The students were also given the opportunity to make any comments about the project without any prompting questions.

Many students commented on the lack of MATLAB preparation: "I thought it was a good assignment that had significance to electromagnetics and MATLAB use, but I was very confused since I have never used MATLAB before." "I really enjoyed doing the MATLAB assignment, but I also found it to be very challenging especially question number 1.15 that one was very hard." "The MATLAB assignment was a good idea, because MATLAB is a very useful program to use and learn. This assignment was very difficult, considering a lot of students are not very familiar with MATLAB and all of its delicacies. I liked the idea of MATLAB, but some of the problems were difficult to complete with my knowledge of the program." "I thought it was a fun project, it helped to learn new things in MATLAB that I didn't know you could do. It was very challenging though typing up the code when some of us are unfamiliar with MATLAB since we've only used it a hand full of times in other classes." "I understand why you would like us to know and use MATLAB in this course but the reality is that most students I know don't have a good if any foundation using MATLAB. It's a great tool and is used a lot outside of the classroom for multiple applications. I think students need to have a MATLAB course to help enhance our understanding of the program."

Even students with substantial previous MATLAB experience, through research projects or internships, found many challenges and learned a lot from the completion of these projects. For example, "I personally have a ton of experience working with MATLAB, both for robotic applications as well as an entire data visualization program for a company" but "I had never been introduced to meshes before and I'm sure that they are a valuable tool that I will use in the future. I learned about plotting vector meshes as well and some other related methods." Also, "Very useful to learn that such tools as surf and quiver3 exists it MATLAB. As well as surfnorm."

Many students acknowledged and appreciated the importance of MATLAB as an essential tool for ECE and the need for gaining or improving MATLAB use and programming familiarity and expertise for students and engineers: "I like what you are trying to do with this project because I do believe that it will be important for all of us to be familiar with MATLAB at some point before we start our careers. I think it was a good call making the assignment extra credit because most of us have very little understanding with MATLAB in the first place." "I like this assignment a lot and you should definitely offer this project in future. It already has help me in another class, ..." "I appreciate the idea of incorporating MATLAB into the curriculum, specifically since MATLAB is so widely used in scientific fields." "I thought it was a nice change from the normal homework. I believe MATLAB is very important for electrical engineers so I am glad we are using it." "I personally think that the MATLAB project was a great idea as in industry I used MATLAB all of the time."

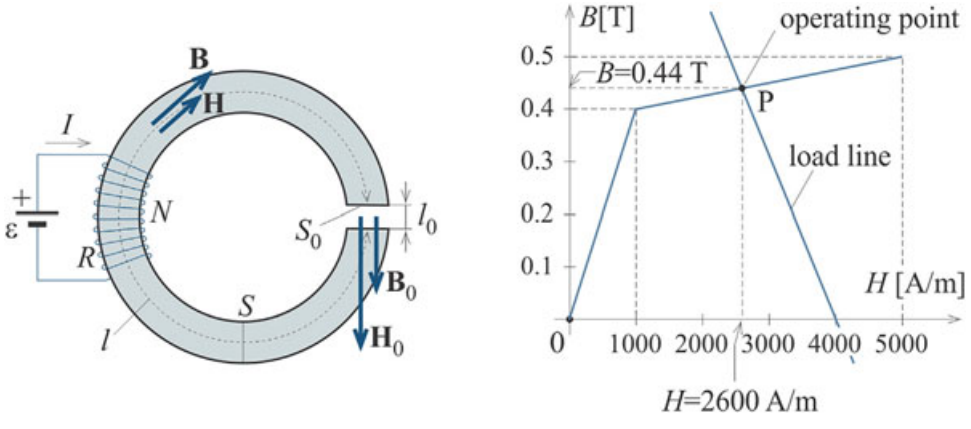

FIGURE 7 Geometry and material properties for Example Problem 6 (from MATLAB assignment 2) in Table 2; also shown is the analytical solution at the operating point for the nonlinear magnetic circuit [28]

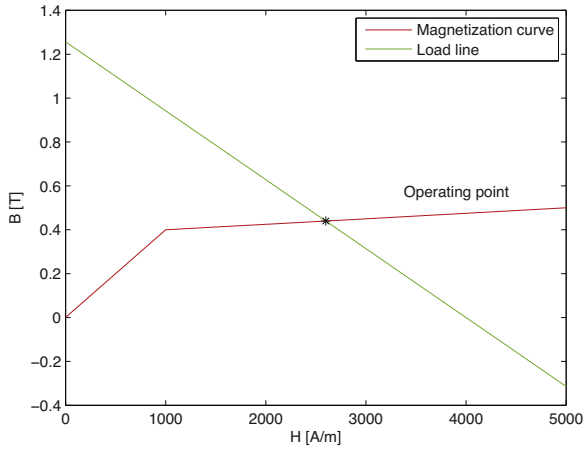

FIGURE 8 Graphical output from the MATLAB code for Example Problem 6 in Table 2, showing the MATLAB solution of the nonlinear magnetic circuit in Figure 7

Some students confirmed that MATLAB exercises helped them develop a stronger intuition and a deeper understanding of electromagnetic field theory, examples, and problems: "Overall I like that you are trying to enhance our knowledge of electromagnetics using MATLAB because I think it's a very important skill to have and it is interesting to see some of the figures and graphs created using MATLAB. It helps visualize how certain changes and other variables affect the output and fields." "I think that this assignment is a really neat way to combine my knowledge of computer programming to a subject that I am not fond of." "I feel that the MATLAB assignment was very useful for giving us a better visual understanding of how Electromagnetics works." "This project helps me a lot about how to use MATLAB to plot and solve questions systematically." "This homework was really useful to understand the problems a lot better. It will be useful to have one or two MATLAB problems with every homework ...." "I think this project was useful but more so for familiarizing us with MATLAB than improving our knowledge of Emag. It was good to reinforce what we already know because I knew what to expect the answers to be."

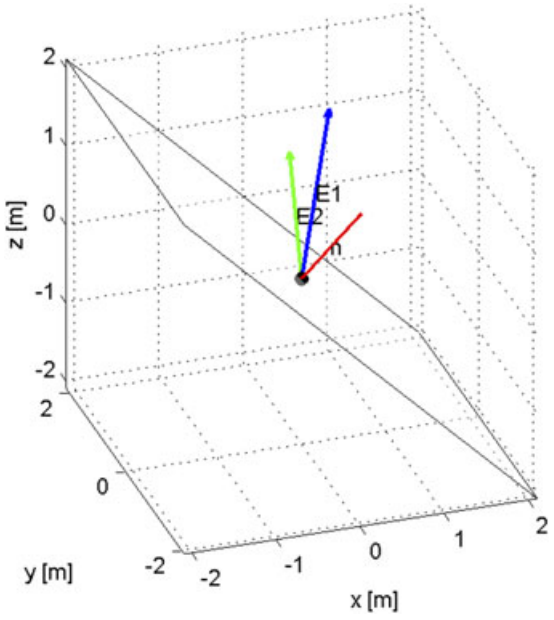

FIGURE 9 An example from MATLAB assignment 1 illustrating the power of MATLAB computation and visualization in electromagnetics (fields): MATLAB computation and visualization of dielectric-dielectric vector field boundary conditions for an arbitrarily positioned (oblique) boundary plane between Media 1 and 2 with arbitrary given permittivities (dielectric constants)

On the other hand, many students stated that MATLAB exercises helped them (instead) gain or improve operational knowledge and skills in concepts and techniques of MATLAB use and programming: "How MATLAB is used in the case of this assignment or other ECE MATLAB assignments, has taught me more about MATLAB than the actual MATLAB class did." "I feel like the MATLAB assignment helped me learn, mainly in MATLAB. My understanding of Electromagnetics did not significantly improve, although the problems required knowledge of electromagnetics. However, my MATLAB knowledge improved greatly because my knowledge prior was very basic." "It enhances my MATLAB programming a lot."

More specifically, the first survey results show that the students felt that the assignment really helped them to improve their knowledge and skills in MATLAB. They also felt that the assignment might be useful in other courses in the curriculum. The students did not feel strongly about the exercises really helping them develop a stronger intuition and a deeper understanding of electromagnetic field theory. This is likely due to the large struggle in learning MATLAB simultaneously with doing the assignment.

After the students had gained the knowledge and skills in the first MATLAB assignment, the second survey shows that they felt less strongly that the assignment improved this area—that is, their knowledge and skills in MATLAB. However, the students did feel relatively strongly that the exercises did indeed help them gain a stronger intuition and deeper understanding of electromagnetic field theory. This supports the idea that the students likely did not gain the understanding benefit due to a lack of knowledge and skills in the required software and programming. This will be something to keep in mind for future iterations of this research. The students also gained an insight into how the skills they improved in programming MATLAB could also apply to other courses as well. This is once again likely to be because the students are no longer focusing on learning the skills of MATLAB, but can instead realize the broader implications of their activities.

In addition, the survey results need to be viewed and judged in the context of the entire RED program and the

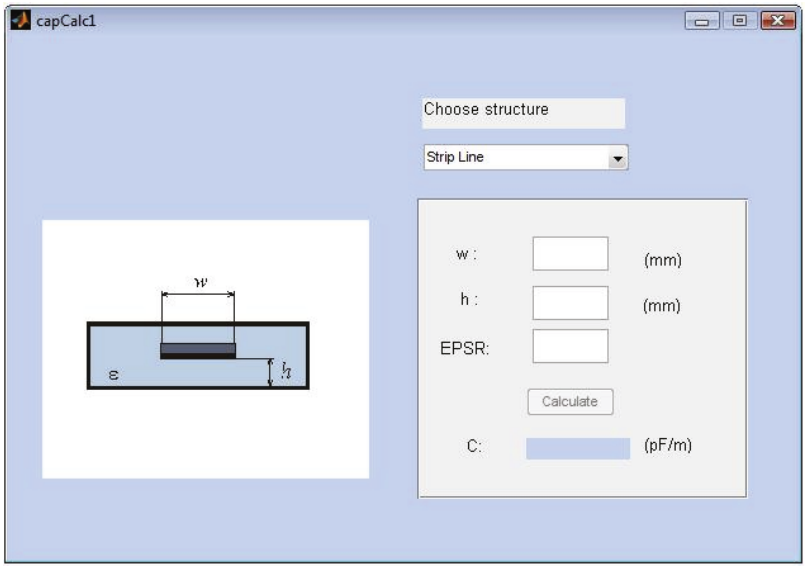

FIGURE 10 Another example from MATLAB assignment 1 illustrating the power of MATLAB computation and visualization in electromagnetics (fields): Capacitance calculator in the form of a graphical user interface (GUI) in MATLAB to interactively calculate and show the capacitance or per-unit-length capacitance of a coaxial cable, microstrip transmission line, parallel-plate capacitor, spherical capacitor, and strip transmission line, respectively, with the names of structures appearing in a pop-up menu

increased workload for the students in the individual core junior-level EE courses and their LSMs, in the associated KI modules between the courses, foundations and professionalism sessions, and team activities. Many students found the "extra" MATLAB assignments overwhelming and overly time-demanding in the context of all the other newly established and required course and program components. "I never had a chance to really try all the problems with multiple other time constraints." "I feel this assignment would have been better to assign when time wasn't so constrained. I barely had any time to work on it and even then I felt very rushed."

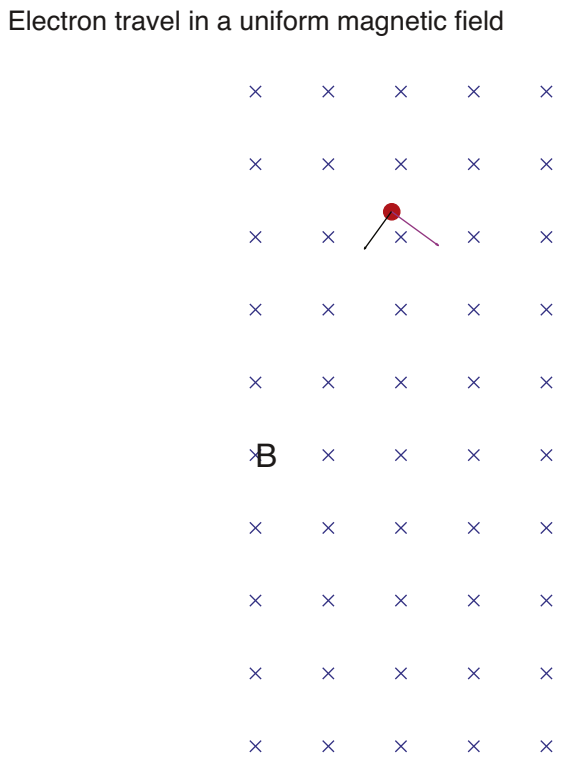

FIGURE 11 An example from MATLAB assignment 2 illustrating the power of MATLAB computation and visualization in electromagnetics (fields): Snapshot of a movie in MATLAB that traces the path traveled by an electron as it enters a uniform time-constant magnetic field

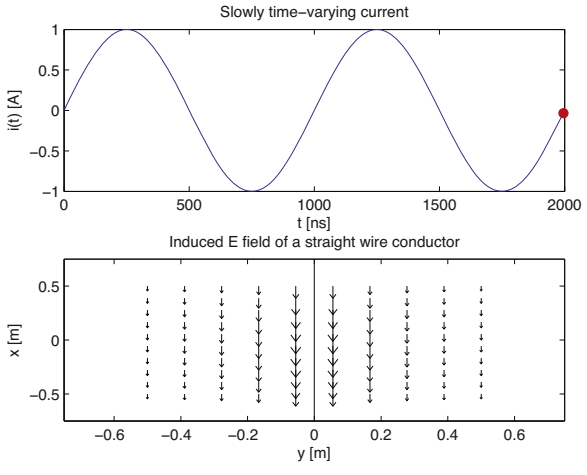

FIGURE 12 Another example from MATLAB assignment 2 illustrating the power of MATLAB computation and visualization in electromagnetics (fields): Snapshot of a movie in MATLAB that shows how the induced electric field intensity vector due to a time-harmonic current in a finite straight wire conductor varies in time and space, along (simultaneously) with the temporal variation of the current (two subplots are viewed simultaneously in the movie)

TABLE 3 Student survey response results, with the average response (AR) and coefficient of variation (CV) presented for each of the two large multi-week MATLAB electromagnetics (fields) assignments.

	Assignment 1		Assignment 2	
Student survey questions	**AR**	**CV**	**AR**	**CV**
1. Did MATLAB Exercises in parallel with traditional written problems and conceptual questions help you develop a stronger intuition and a deeper understanding of electromagnetic field theory, examples, and problems?	1.65	0.66	2.11	0.43
2. Did MATLAB Exercises help you find Electromagnetic Fields more attractive and likable?	1.46	0.73	1.50	0.86
3. Did MATLAB Exercises help you improve your knowledge and skill of using MATLAB, that is, help you build and enhance the understanding and command of MATLAB syntax, functionality, and programming, in the framework and cause of electromagnetics?	2.08	0.44	1.89	0.60
4. Did MATLAB Exercises allow you to gain some operational knowledge and skills in concepts and techniques of MATLAB use and programming that could potentially be used and imple-mented in other courses in the curriculum?	1.98	0.44	2.18	0.44
5. Did you find this MATLAB Project assignment challenging?	2.60	0.29	2.42	0.32

Finally, in addition to the above qualitative analysis of the new approach and project results through student feedback surveys, we also used the results on the Electromagnetics Concept Inventory (EMCI) [10,27]. Namely, the instrument was administered 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 Fall 2016, was 2.5 times higher than the score by students taught without MATLAB Creativity Thread and MATLAB programming assignments.

4 | CONCLUSIONS

This paper has presented and discussed the inclusion of computer-assisted MATLAB-based instruction and learning in the electromagnetics (fields) course and LSMs within the creativity thread of the RED project in the ECE Department at Colorado State University. Creativity class sessions were followed by two comprehensive and rather challenging multi-week homework assignments of MATLAB problems and projects in electromagnetics. This is enabled by a unique and extremely comprehensive collection of MATLAB tutorials, exercises, projects, and codes, developed by one of the faculty team members. These materials exploit technological and pedagogical power of MATLAB software as a general learning technology and constitute a modern tool for learning electromagnetics via computer-mediated exploration and inquiry. The assignments required the students to solve problems and generate results presented in figures, diagrams, movies, and animations, by writing, testing, and executing their own MATLAB programs as well as running existing codes. The goal for students as learners is to gain and solidify the knowledge of fundamentals of electromagnetic fields using MATLAB and to build and enhance the understanding and command of MATLAB syntax, functionality, and programming in the framework of electromagnetics.

The principal difference of the presented approach when compared to the previous studies is the focus on introduction of MATLAB programming of electromagnetics performed by students, whereas in the previous reports, the students primarily conducted virtual experiments interacting with a GUI based on a MATLAB platform rather than writing their own MATLAB programs. The difference is also in the scope of the engaged computer-assisted MATLAB-based instruction and learning of electromagnetics in terms of topics, concepts, and techniques, with our developed MATLAB tutorials, exercises, and projects covering and reinforcing practically all important theoretical concepts, methodologies, and problem-solving techniques in electromagnetics and most of the previous studies focusing on a much smaller subset of topics. In addition, none of the previous studies with a similar intent, have, to the best of our knowledge, reported the results of the study in terms of analyses of the impact of the proposed and implemented approaches on students' performance, learning, mastery, attitude, success, and satisfaction that would enable comparison with the study presented in this paper.

The paper has presented and discussed some example problems from the Creativity Thread MATLAB assignments related to some of the most important pedagogical features of MATLAB pertaining to electromagnetic fields instruction/learning, such as manipulation and visualization of vectors and multivariable spatial functions, numerical analysis, and symbolic programming. It has shown the benefits of solving the problems and studying the topics both analytically and

using MATLAB. The paper has also discussed how MATLAB assignments enable engagement of students' learning styles less frequently reached by typical lecture type of teaching and standard simulation software and tools, including visual, active, global, and inductive learning styles, most often helping several different categories of student learners at the same time.

Due to multifaceted changes introduced in association with the RED project in the junior year of the EE program at CSU in the Fall of 2016, we concluded that a quantitative analysis of how these MATLAB assignments affected the students' grades was not appropriate or feasible. Instead, as done in other prior studies, the results of this project were qualitatively analyzed using data from surveys given to the students at the end of each MATLAB assignment. The students who participated in the MATLAB exercises and surveys had mixed opinions about whether it was helpful to their personal understanding and mastery of the material. Overall, however, the students had relatively positive feedback for the assignments. There was a rather large percentage (72% on the first assignment and 63% on the second) of the students who even took the time to provide comments in addition to answering the five questions on the survey. For example, of the students who commented, 19 of the 28 had positive things to say about the first assignment. The majority of the negative comments all stem from a perceived lack of previous experience in MATLAB that was nearly universal among the students. But this is exactly why these MATLAB sessions and assignments were included, through the electromagnetics course, in the creativity thread of the RED project, that is, to improve students' operational knowledge and skills in concepts and techniques of MATLAB use and programming, which can then be utilized in other courses in the curriculum, as well as in research activities, senior design (capstone) projects, etc. In addition, students' results on the Electromagnetics Concept Inventory assessment instrument showed great improvement when compared to the approach with no MATLAB sessions and assignments of the previous year.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation under grant EEC-1519438. The authors would like to thank Andrea Leland for her editorial changes that have greatly improved the presentation of this work.

ORCID

Branislav M. Notaroš http://orcid.org/0000-0002-5755-961X

REFERENCES

1. G. Apaydin and L. Sevgi, *A MATLAB-based virtual tool for simulations of wave propagation inside a parallel-Plate waveguide [Testing ourselves]*, IEEE Antennas Propag. Mag. **59** (2017), 100–105.
2. B. Beker, D.W. Bailey, and G. J. Cokkinides, *An application-enhanced approach to introductory electromagnetics*, IEEE Trans. Educ. **41** (1998), 31–36.
3. L. E. Bernold, J. E. Spurlin, and C. M. Anson, *Understanding our students: A longitudinal-study of success and failure in engineering with implications for increased retention*, J. Eng. Educ. **96** (2007), 263–274.
4. J. M. Bértolo et al., *General purpose software package for electromagnetics engineering education*, Comput. Appl. Eng. Educ. **10** (2002), 33–44.
5. T. Chen et al., *Mastering the Core Competencies of Electrical Engineering through Knowledge Integration*, Proceedings of the 123rd American Society for Engineering Education Annual Conference & Exposition—ASEE2016, New Orleans, LA, 2016.
6. M. Chetty, S. Hu, and J. Bennett, *An interactive java-based educational module in electromagnetics*, Int. J. Electr. Eng. Educ. **40** (2003), 79–90.
7. M. de Magistris, *A MATLAB-based virtual laboratory for teaching introductory quasi-stationary electromagnetics*, IEEE Trans. Educ. **48** (2005), 81–88.
8. V. Demir and S. Kist, *Matlab demonstrations for concepts in electromagnetics*, 31st International Review of Progress in Applied Computational Electromagnetics (ACES), Williamsburg, VA, 2015, pp. 1–2.
9. I. D. Dinov, J. Sanchez, and N. Christou, *Pedagogical utilization and assessment of the statistic online computational resource in introductory probability and statistics courses*, J. Comput. Educ. **50** (2008), 284–300.
10. D. L. Evans et al., *Progress on Concept Inventory Assessment Tools*, Proceedings of the 33rd ASEE/IEEE Frontiers in Education Conference—FIE 2003, pp.T4G.1-8, 2003, Boulder, CO.
11. H. G. Espinosa and D. V. Thiel, *MATLAB-Based interactive tool for teaching electromagnetics [Education corner]*, IEEE Antennas Propag. Mag. **59** (2017), 140–146.
12. R. M. Felder and R. Brent, *Understanding student differences*, J. Eng. Educ. **94** (2005), 57–72.
13. R. M. Felder and L. K. Silverman, *Learning and teaching styles in engineering education*, Eng. Educ. **78** (1988), 674–681.
14. R. M. Felder and J. Spurlin, *Applications, reliability and validity of the index of learning styles*, Int. J. Eng. Educ. **21** (2005), 103–112.
15. R. M. Felder, R. Brent, and M. J. Prince, *Engineering instructional development: Programs, best practices, and recommendations*, J. Eng. Educ. **100** (2011), 89–122.
16. A. W. Glisson and A. Z. Elsherbeni, *An interactive 1D matlab FDTD code for education*, Comput. Appl. Eng. Educ. **9** (2001), 136–147.
17. K. C. Gupta, T. Itoh and A. A. Oliner, *Microwave and RF education-past, present, and future*, IEEE Trans. Microwave Theory Tech. **50** (2002), 1006–1014.
18. J. F. Hoburg, *Can Computers Really Help Students Understand Electromagnetics?* Joint MMM-Intermag Conference Proceedings, Pittsburgh, PA, 1991.

19. S. R. H. Hoole, *A course on computer modeling for second or third year engineering undergraduates*, IEEE Trans. Educ. **36** (1993), 79–89.
20. M. F. Iskander, *NSF/IEEE CAEME center: An exciting opportunity to align electromagnetics education with the nineties*, Comput. Appl. Eng. Educ. **1** (1992), 33–44.
21. M. F. Iskander, *Technology-based electromagnetic education*, IEEE Trans. Microwave Theory Tech. **50** (2002), 1015–1020.
22. M. F. Iskander et al., *Development of multimedia modules for education*, Comput. Appl. Eng. Educ. **3** (1995), 97–110.
23. M. F. Iskander et al., *Interactive multimedia CD-ROMs for education*, Comput. Appl. Eng. Educ. **4** (1996), 51–60.
24. T. A. Litzinger et al., *A psychometric study of the index of learning Styles*©, J. Eng. Educ. **96** (2007), 309–319.
25. A. A. Maciejewski et al., *A Holistic Approach to Transforming Undergraduate Electrical Engineering Education*, Special Section, Innovations in Electrical and Computer Engineering Education, IEEE Access, 2017, Vol. 5, pp. 8148–8161.
26. C. Mias, *Electronic problem based learning of electromagnetics through software development*, Comput. Appl. Eng. Educ. **16** (2008), 12–20.
27. B. M. Notaros, *Concept Inventory Assessment Instruments for Electromagnetics Education*, Proceedings of 2002 IEEE Antennas and Propagation Society International Symposium, Vol. 1, pp.684–687, San Antonio, TX, 2002.
28. B. M. Notaroš, *Electromagnetics*, Upper Saddle River, NJ: Pearson Prentice Hall, 2010.
29. B. M. Notaroš, *MATLAB®-based electromagnetics*, Upper Saddle River, NJ: Pearson Prentice Hall, 2013.
30. B. M. Notaroš et al., *Work in progress: Introducing MATLAB-Based Instruction and Learning in the Creativity Thread of a Novel Integrated Approach to ECE Education*, Proceedings of the 124th American Society for Engineering Education Annual Conference & Exposition—ASEE2017, Columbus, OH, 2017.
31. National Research Council, *How people learn: Brain, mind, experience, and school*. Expanded edition. National Academies Press, Washington, D.C. 2000.
32. O. Ozgun and L. Sevgi, *VectGUI: A MATLAB-based simulation tool [Testing ourselves]*, IEEE Antennas Propag. Mag. **57** (2015), 113–118.
33. J. C. Rautio, *Educational use of a microwave electromagnetic analysis of 3-D planar structures*, Comput. Appl. Eng. Educ. **1** (1993), 243–254.
34. J. C. Rautio, *The impact on education of widely available commercial 3-D planar electromagnetic software*, Comput. Appl. Eng. Educ. **8** (2000), 51–60.
35. A. A. Read, *Computers and computer graphics in the teaching of field phenomena*, IEEE Trans. Educ. **33** (1990), 95–103.
36. S. Sanz, M. F. Iskander, and L. Yu, *Development of an interactive multimedia module on antenna theory and design*, Comput. Appl. Eng. Educ. **8** (2000), 11–17.
37. S. Selleri, *A MATLAB experimental framework for electromagnetic education*, IEEE Antennas Propag. Mag. **45** (2003), 86–90.
38. L. Sevgi, *Teaching electromagnetics via virtual tools*, 2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, Vancouver, BC, 2015, pp. 1021–1022.
39. E. Seymour and H. Hewitt, *Talking about leaving: Why undergraduates leave the sciences*, Boulder, CO: Westview Press, 1997.
40. W. L. Stutzman, *Integration of the personal computer into undergraduate electromagnetic courses*, Comput. Appl. Eng. Educ. **1** (1993), 223–226.
41. F. T. Ulaby and B. L. Hauck, *Undergraduate electromagnetics laboratory: An invaluable part of the learning process*, Proc. IEEE, **88** (2000), 55–62.
42. R. J. Wlodkowski, *Enhancing adult motivation to learn: A comprehensive guide for teaching all adults*. John Wiley & Sons, San Francisco, CA 2011.

B. M. NOTAROŠ received the Dipl.Ing (BS), MS, and PhD degrees in Electrical Engineering from the University of Belgrade, Belgrade, Yugoslavia, in 1988, 1992, and 1995, respectively. From 1996 to 1999, he was an assistant professor in the School of Electrical Engineering at the University of Belgrade. He spent the 1998–1999 academic year as a visiting scholar at the University of Colorado at Boulder. He was an assistant professor, from 1999 to 2004, and associate professor, from 2004 to 2006, in the Department of Electrical and Computer Engineering at the University of Massachusetts Dartmouth. From 2006 to 2012, he was an associate professor in the Department of Electrical and Computer Engineering at Colorado State University, where he is currently a professor and University Distinguished Teaching Scholar, as well as director of Electromagnetics Laboratory. His research interests and activities are in computational electromagnetics, higher order numerical methods, antennas, scattering, microwaves, metamaterials, characterization of snow and rain, surface and radar precipitation measurements, RF design for MRI at ultra-high magnetic fields, and electromagnetics education. His publications include more than 230 journals and conference papers, and three workbooks in electromagnetics and in fundamentals of electrical engineering (basic circuits and fields). He is the author of textbooks *Electromagnetics* (Prentice Hall, 2010), *MATLAB-Based Electromagnetics* (Prentice Hall, 2013), and *Conceptual Electromagnetics* (CRC Press, 2017). Dr. Notaroš is fellow of the IEEE and of the Applied Computational Electromagnetics Society (ACES). He served as general chair of the 2018 International Applied Computational Electromagnetics Society Symposium – ACES2018, March 25–29, 2018, Denver, Colorado, USA, and of the 11th International Workshop on Finite Elements for Microwave Engineering – FEM2012, June 4–6, 2012, Estes Park, Colorado, USA. He serves as general chair of the 14th International Workshop on Finite Elements for Microwave Engineering – FEM2018, September 10–14, 2018, Cartagena de Indias, Colombia. He is associate editor for the IEEE Transactions on Antennas and Propagation,

and served as guest editor of the Special Issue on Finite Elements for Microwave Engineering, Electromagnetics, Vol. 34, Issue 3–4, 2014. He serves on the board of directors of ACES, as ACES secretary, and as vice-chair of the US National Committee Commission B of the International Union of Radio Science (URSI), for which he previously served as technical activities chair (2015–2018). He was the recipient of the 2005 IEEE MTT-S Microwave Prize (best-paper award for IEEE Transactions on MTT), 1999 IEE Marconi Premium (best-paper award for IEE Proceedings on Microwaves, Antennas and Propagation), 1999 URSI Young Scientist Award, 2005 UMass Dartmouth Scholar of the Year Award, 2004 UMass Dartmouth College of Engineering Dean's Recognition Award, 2010 Colorado State University College of Engineering George T. Abell Outstanding Teaching and Service Faculty Award, 2012 Colorado State University System Board of Governors Excellence in Undergraduate Teaching Award, 2014 Colorado State University Provost's N. Preston Davis Award for Instructional Innovation, 2012 IEEE Region 5 Outstanding Engineering Educator Award, 2014 Carnegie Foundation for the Advancement of Teaching Colorado Professor of the Year Award, 2015 American Society for Engineering Education ECE Distinguished Educator Award, and 2015 IEEE Undergraduate Teaching Award.

R. MCCULLOUGH received BS degrees in Electrical Engineering and Applied Physics at Colorado State University in 2017. He also holds a BEd degree from the University of Toledo. He worked as a teacher for 5 years before returning to get a degree in Electrical Engineering in 2014. He taught Physics and Chemistry at the high school level in the U.S. and in Namibia through the Peace Corps. At Colorado State University, he worked as a research assistant in both engineering education and magnetic resonance imaging RF coil design.

S. B. MANIĆ was born in Belgrade, Serbia, in 1986. She received the BS degree in 2010 from the Department of Electronics, School of Electrical Engineering, Belgrade University, Serbia. She is a PhD student, since 2010, at the Department of Electrical and Computer Engineering, Colorado State University, where she has worked as both graduate research assistant in the Electromagnetics Laboratory and graduate teaching assistant/instructor for electromagnetics and other electrical engineering courses. Her interests are in computational electromagnetics, higher order surface integral equation method of moments, higher order finite element method, iterative solvers, and weather precipitation modeling.

A. A. MACIEJEWSKI received the BSEE, MS, and PhD degrees from The Ohio State University in 1982, 1984, and 1987. From 1988 to 2001, he was a professor of Electrical and Computer Engineering at Purdue University, West Lafayette. He is currently a professor and department head of Electrical and Computer Engineering at Colorado State University. He is a fellow of the IEEE. A complete vita is available at: http://www.engr.colostate.edu/~aam

How to cite this article: Notaroš BM, McCullough R, Manić SB, Maciejewski AA. Computer-assisted learning of electromagnetics through MATLAB programming of electromagnetic fields in the creativity thread of an integrated approach to electrical engineering education. *Comput Appl Eng Educ*. 2019;27:271–287. https://doi.org/10.1002/cae.22073