Improvements in Undergraduate Electromagnetism Courses by Designing Experiences of Inquiry and Reflection

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Abstract
In this research study, the effect of reflective practices in improving undergraduate students’ learning of electromagnetism is presented. Most engineering students are trained to be problem solvers and detail oriented. Correspondingly, undergraduate level electromagnetism courses bring challenges of visualization and abstraction for most students. Learning by repetition, memorizing equations, and practicing problems without deeper thinking or reflecting are some of the superficial learning techniques that many students may adopt. Moreover, several students face difficulties drawing connections between physics concepts and the equations “formulas” they use on a day-to-day basis.

In this work, students’ reflections from two different electromagnetism courses were examined and a sample analysis of two reflection questions are presented. One set of students were trained to use the basic Maxwell’s equations and the relevant physics and mathematical perspectives (with a inquiry based and reflective approach). while the other set were focused on developing a conceptual understanding of electromagnetism “with connected concepts and practical approach and applications that student can relate to”. The second approach represents a more electromagnetic literacy approach. By analysing and contrasting these perspectives we try to find appropriate mergers of learning techniques that would be valuable for all students seeking to develop a strong fundamental understanding of electromagnetism.

Introduction
Electromagnetism (EM) courses are historically considered to be one of the most challenging courses in the electrical engineering curriculum [1-14]. Some students feel the course is challenging due to a large disconnect between abstract concepts and real-life/engineering experiences [2-4]. Others feel the heavy emphasis on calculus and physics [4,5] is the deterrent. While both these student groups are attempting to learn and relate to fundamentals of electromagnetism, it is understood that a vast majority of the student group attempts to learn electromagnetism just by using equations and solving the assigned problems [5,6]. This example-focused learning approach, does not help students to make meaningful connections between concepts and methods, nor between equations and conceptual visualization. Thereafter, the example-focused approach, while may be effective in lower level undergraduate courses, is seemingly ineffective when students attempt to learn courses which require them to imagine, think, make abstract connections, and visualize electric and magnetic fields in space [4-7].

Many different instruction techniques have been implemented to address the connectivity gap between the student’s learning approach and required conceptual maturity for electromagnetism
courses, such as team active-learning [1,8,9], technology-based learning [10,11], group discussions, experiential learning [6], and project based learning [12-14]. Each of these techniques brings about a thematic change in the way students interact with one another and experience the course material. However, in many typical classes students aren’t necessarily exploring, questioning, and learning within the classroom setting [15,16]. These observations have led us to reframe our electromagnetism instruction to be active learning via inquiry-base within the classroom setting.

In this paper the effectiveness of reflective learning in an inquiry-based approach initiated by John Dewey is explored for undergraduate level electromagnetism courses. Our motivation in choosing this technique over several others lies mainly in the fact that students need to use their time in the classroom, thinking, questioning, and exploring while they are working with their peers and the instructor. In this work, a contrast in the implementation of reflective practices in a calculus or equation-based and a non-calculus or conceptual electromagnetism course is presented.

**Motivation**

Our first experience of introducing reflective practices in electromagnetism and experiencing students’ learning in such an environment was in a course called Electromagnetism for non-electrical engineers. This course focuses more on engineering and technological literacy. It connects the ideas in coherent conceptual ways rather than competency approach which mostly emphasises calculus, physics, and important definitions and equations that are dominant in third year electromagnetism. The EM for non-electrical engineers (non-calculus based) deals with almost all aspects of EM, including conceptual and practical issues of the field without any required calculus. The class covers basic classical electromagnetism, moves to the later part of the 19th century and the early 20th century. There are discussions about electrodynamics, ideation of Quantum mechanics, Special relativity, some basics of General theory of relativity, and an introduction to quantum computing. The class has been very popular with all engineers (some EE students have chosen to take it even though it does not help them with their graduation).

The EM for non-majors (non-calculus) is designed and delivered as a reflective class. Students have to do one or two reflections per class period, weekly/bi-weekly assignments, and final projects. The most interesting finding over the last few years has been the fact that in majority of the reflections the students in the EM for non-majors show more interest, passion, and are always trying to achieve in-depth understanding of the concepts and connected ideas than in the EM for majors.
This class helped us to realize a successful way of asking the students to not just do but think about the problem. Our findings from the EM for non-majors led us to offering a reflective form of EM for majors (calculus-based EM). The calculus-based EM traditionally focuses more on the mathematical formulation and vector calculus-based approach towards Maxwell’s equations, waves and transmission lines. In our new approach there are more interactive and team based learning activities, with more emphasis on thematic focus on the process, application, and connection of the basics of the material. Due to the interactive nature of this class, the class does not allow us to cover all the details that traditional EM classes do. We cover the following: i) Review of multivariate calculus, coordinate systems, and space analysis tools as well as vector calculus. ii) Electrostatics iii) Magnetostatics iv) Maxwell’s equations v) Wave propagation and applications, and normal incidence vi) Transmission lines. However, the class is designed to minimize focus on theoretical derivations. The goal is to facilitate students’ learning so they can gain knowledge, practice the basics and connections, and gain confidence to learn on their own and comfortably to other EM classes.

This paper is a report of our efforts to bring the same thematic practice that has been successful in our non-calculus class to the calculus-based class. The goal was that the new delivery of the reflective part with in-class activities would help better in-depth understanding of important concepts, technical details, and ideas in EM. In addition, we would like to see if the method would initiate more in-depth understanding and more connection to the material. Ultimately, it is expected that through the process of reflection, and class interactions, students identify their personalized style of learning and develop the confidence and ability to recall or relearn any concept in the future. Finally, the question that we would like to find is “do reflective practice help students to have better connections and understanding of EM for the calculus-based EM class?”

**Deweyan model for inquiry based process**

Our method of reflective activities [16-18] and assessment is based on John Dewey’s philosophy of inquiry-based learning [19-22]. In this pedagogy, each individual is held accountable for his/her explorations in the cycles of learning. The cycle of learning begins with a question, a curiosity, a felt discomfort. This is followed by an attempt to locate the source of their discomfort and doubt and seek possible solutions. On identification of possible solutions, each individual goes through a cycle of deliberation: weighing factors in favor of (or against) their possible decisions and eventually the individual forms a set of beliefs or disbeliefs associated with the question or discomfort. It is important to realize that while the individual is learning through each stage of this cycle, it is expected that their personal engagement with the learning process will propel them to engage in greater depth everytime they encounter the same questions/doubts. Additionally, heavy emphasis is placed on the process of learning instead of
the end result. Thus, the Deweyan model of learning tends to be a personalized process for each individual.

**Deweyan model in the classroom**

The best way to implement Dewey’s inquiry-based pedagogy in each class, and more importantly, lead each student in a cycle of personal inquiry, is for students to engage in reflections. Reflective activities can include reflective questions, step by step descriptions of problems that students need to solve, as well as reasoning and discussion of their method and answer. Students can verbalize their thoughts, engage in critical thinking, and connect details of the process and method at the same time through reflective practice and critical evaluations.

It is expected that in every reflection, the student goes through a cycle or series of personal questions and debates attempting to learn, resolve, and create personal stories. In addition, students reflect on their personal narrative of the meaning, the connection, and the methodology that they are experiencing [18]. During in-class reflective activities, the student is exposed to the views of other team members. They are encouraged to think, discuss, share, and write their own reflections. Then the student needs to critically evaluate his/her choices, and create an informed decision. This is not a trivial process. In practice, we try to follow students development in answering questions, dealing with the difficulties of the activity, and finding meanings throughout the term. In addition, frequent feedback is provided to the student and the class. Some of the good answers are discussed and analyzed to help students understand possible perspective and views that are presented by their peers. As the students’ critical thinking improves, their learning and integration of the knowledge improves, and the texture of their reflections and details of their problem solving will improve. This is discussed with the class over time and they are encouraged to keep on keeping on and exploring and examining their knowledge and capabilities.

**Implementation of reflective practices**

Initially engineering students hesitate to engage in true reflective and interactive activities since they are very grade sensitive and are afraid of making mistakes. In the proposed method, students’ work is always collected, reviewed, and timely feedback is provided to the class. In such an environment we create a more inclusive and reflective approach such that students would share their ideas and thoughts without the threat of losing points and not succeeding in the class. Our research [17-19] shows that for many students, in the inclusive environment, the mistakes are perhaps more of a learning experience than the successes in the daily activities. When students focus on their thoughts, experiences, application of knowledge and take actions, knowing that the mistakes will not really damage their grade, they engage in experimentation, and finding their ways and exploring new ways. This process, together with timely feedback, allows students to learn to label mistakes as a vehicle for growth and not failures. At the
beginning of the class, the more grade sensitive students do get nervous and anxious. Our experience shows that if we calm them and let them try, together with a non-punishing grading process, they will eventually find their way and fit their style to more engagement and the learning process.

Our implementation of reflective practices is based on not overwhelming students with too much information, revisiting difficult subjects from different angles, and by different activities to allow the students to find their way to connect and reflect on their learning. This includes the time to allow gradual maturing by the students to understand the process of their learning. Finally, based on the reflections provided by the student, there is more evidence of their awareness and eagerness to realize the value of lifelong learning.

In our courses, during each lecture, students engage in activities/problem solving and discuss their thoughts, ideas and reflections with their teams. Through these reflections, the students review and summarize their learning from previous lectures and at the same time they actively engage in the process of thinking and deliberation within the classroom.

A day in the non-calculus based class
Every class, starts with a brief review, open discussions and Q/A of the last class. In this section some of the major finding about the previous in-class activities will be reviewed and discussed. Then the new material/concepts/applications will be presented. The class needs to experience the material, think, discuss and reflect on the new material. The material consist of faculty lectures, and discussions, developing new concepts and discussing the relationship to the previous and future concepts, showing video modules with faculty annotation, making connections with other known materials and classes, and posing various investigative/thinking questions. In this class the material may have calculus, and vector calculus but the student will not be asked to do calculus. They are asked to reflect on what they understand of the concepts and applications. Each class will have a 10-15 minutes in-class activity to facilitate their discussions, learning, and engaging the students in ideation, design, and connecting and expanding on their knowledge.

A day in the calculus-based class
This class starts with review of the material, and help students make conceptual connection. In the first section the issues and difficulties that the students had in the previous in-class activities will be addressed and clarified. There will be a Q/A session to help student ask live questions. The class will be introduced to regular EM calculus based material. Then there will be discussion and activity session where students will work with their team on a problem, conceptual development or application of the material. The purpose is for the students to write personal work, reflection, and detailed work to show their understanding and difficulties they
have with the material. It should be noted that many of the games in this class do contain working with and thinking about mathematical concepts and visualizations. There are quarter of the in-class activities that would ask the students to reflect on an experiment, demonstration that they see during the class.

In both of the classes the in-class activities are called “Games” the idea is to encourage students to feel free to show what they think and how they think, and reflection on where they are with their conceptual development, practical capabilities, learning, and thinking.

At the beginning the EM for major students try to write everything they remember such as equations and other memory-based knowledge. The students are reluctant to respond to reflective activities. They possess a fear of bad grades and failing on the in-class activities. They start being nervous, since we ask them to think, argue and find a solution. Additionally, the students are unsure if their work is up to the expectation of the instructor. One of the sources of their fear is the fact that in these classes students are not facing one-sided information that constitute traditional lectures. This fear is expected. The students are communicating their knowledge and aren’t necessarily engaging in thinking deeply about the essence of learning and doing. However, reflections do not necessarily have only one correct answer. Therefore, over the course of the semester, the students need to willingly communicate and express their perceptions in their work. Our research shows that by reducing the threat of bad grades and creating a safe classroom environment, students are willing to communicate, ask, and learn from one another. This is achieved by systematically providing constructive feedback, and encouraging students in their journeys.

**Evaluation Process**

As discussed, our sample space includes two student groups. The first set of students are engineers who are taught EM with emphasis on equations and problem solving. The second set of students are engineers who are learning about EM from a technological literacy and application perspectives. They learn important concepts without the demand of mathematical rigor. For each group, daily reflective activities were assessed over the entire semester. A phenomenographic [24-26] approach was used to assess the student’s conceptual understanding and detail. For this study, we have evaluated reflections for two different in-class activities from both groups of students.

In the first early phase activity, the students were asked to define capacitors, explain their behavior and describe possible applications and utility for EM. Since the students have learned about capacitors in several courses this reflection was used as a benchmark of their prior knowledge and learning. In the second activity, the students understanding of Faraday’s law was evaluated. While the students should have learned this concept in prior physics courses, this was
the first time they could actually verbalize the concept and learn more about it. To facilitate this, student’s observed a few experiments/demos such as a magnet dropping through a copper pipe, and an electromagnetic ring launcher besides the lecture. They were then asked to explain the phenomenon associated with their experimental observations in their own words.

Research Questions
To be effective we needed to pose a focused set of research questions. Common questions such as “Are reflective practices effective and sufficient in bridging the gap between physics concepts and abstract mathematical formulation?” and “Can improved connectivity lead to improvements in the students’ learning and perception of electromagnetism?” are valid and necessary. However, these questions remain significant in almost all engineering courses. The major question for us was, would the reflective practice engage, excite and initiate more thoughtful ideas and discussions in the EM for major students?

Research Findings
Several parameters play into the student’s reflections. Some students prefer to engage more in team discussions and these are equally valuable though not easily measurable. As reflective practitioners, we assess the student’s approach towards concepts and the depth of connectivity in their writing. Correspondingly, we define three stages of student reflections [27-32] for our evaluation. These are:

Stage I: Student’s rely on their memory and repeat their observations without major engagement. They are verbalizing equations and stating facts.

Stage II: Student’s aren’t fully aware of their learning but are attempting to connect their ideas using text, figures, and equations.

Stage III: Students have personalized their learning and are expressing their ideas, thoughts, and questions. They are thinking about their own thinking.

Based on these stages, and using a phenomenographic approach, the students’ responses for our research questions were categorized.

Understanding physical concepts of devices
For our first research question, the students were asked to define a capacitor, its functionality and applications. The students could use diagrams, equations and any other way of describing what they knew from prior experiences. Early answers included two plates, storage of charge, stores voltage, stops current etc. One must note that this research question was asked in the introductory weeks of the semester. The question was chosen such that the students had
pre-existing knowledge about it and could thus make attempts to connect their ideas and provide a story even though they weren’t well familiarized with the process of reflective writing. While students verbalize differently due to their experiences, the common phrases from each group of students may be found in Table 1.

<table>
<thead>
<tr>
<th>Stages</th>
<th>Calculus-based students</th>
<th>Non-calculus students</th>
</tr>
</thead>
<tbody>
<tr>
<td>I: Facts and Observations</td>
<td>Stores electrical energy or voltage or charge, equation and diagram</td>
<td>Device that accumulates electric charge, stores energy</td>
</tr>
<tr>
<td>II: Reasoning with Details</td>
<td>Device with electric field between charged parallel plates, Stops current, Charge separation</td>
<td>Stores energy in electric field, dampen changes in potential</td>
</tr>
<tr>
<td>III: Personalization and Connected Visualization</td>
<td>Resists changes in voltage, application examples, I think...</td>
<td>Resists changes in voltage/potential, require time to charge and discharge, application examples</td>
</tr>
</tbody>
</table>

Table 1: Summary of phrases used by students to describe a capacitor

Since students in both the courses had prior background in circuits and devices, what we found was that a major set of students were envisioning capacitors to be charge storage devices wherein energy was stored by creation of an electric field between two plates. Besides this, many students were able to verbalize the capacitor to be a device that resisted instantaneous changes in voltage and thus its application in filters or surge protection devices. Between the two sets of students, we found that almost half of the non-calculus EM students and 80 percent of the calculus-based EM students were personalizing their descriptions. From Fig. 1, we also see that there were approximately an equal number of students (less than 25 percent) in Stages I and II in the non-calculus EM course. It is noteworthy that many students were already in Stage III.
Understanding Faraday’s Law
To gather knowledge about the students' depth of understanding, Faraday’s law, a concept that they learned in detail during the course, was selected. For this question, the students were shown experimental demonstrations involving Faraday’s Law. After the demonstrations and discussions, they were asked to explain what they saw in the demonstration, the associated phenomena and how it could be used to explain the demonstration. The main phrases that the students reported are summarized in Table 2. It must be noted that at the time this question was posed, the students were well acquainted with the process of reflection and understood the effectiveness of reflections in their communication. This is apparent from Fig. 2. Here we see that in both courses there are very few students in Stage I and while several of the students are in Stage II almost 40 percent of the students are in Stage III. This implies that the students are self-aware and seeking to own their knowledge. They are no longer repeating the facts but are willing to report their thoughts and even ready to create an error in their descriptions.
<table>
<thead>
<tr>
<th>Stages</th>
<th>Calculus-based EM Students</th>
<th>Non-calculus EM Students</th>
</tr>
</thead>
<tbody>
<tr>
<td>I: Facts and Observations</td>
<td>Wire moved up, opposed the force</td>
<td>Description of experimental setup</td>
</tr>
<tr>
<td>II: Reasoning with Details</td>
<td>Induced voltage/emf/flux/H, multimeter reading, equations, changing magnetic field/flux</td>
<td>Equations, induced emf, infinite loops and closed path</td>
</tr>
<tr>
<td>III: Personalization and</td>
<td>Connected equations/description and images, eddy currents</td>
<td>Flux change, discussion on the equations and images</td>
</tr>
<tr>
<td>Connected Visualization</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Summary of phrases or methods used by students to describe Faraday’s law and the associated demonstration

Fig. 2: Trends in student reflections for a question based on Faraday’s law

**Student Observations and Critique**

Students in the non-calculus EM course are primarily engineering students who elect to take this course as an elective. In the beginning the students are equation focused, since most engineering classes train them that way. However, as we work with them and communicate our goals and the need, purpose, and process of reflections [33], they become more confident and move towards
voicing their opinions. Within this class, there are generally two distinct groups of students. The first one does not believe reflections work. So, they participate only to get the grade. As they get feedback, and see other comments to their peers, and as they see encouragements for their more in depth answers and discussion, they start adapting to the process and develop their way of doing things.

The second major group are those who do the reflections and enjoy it but do not believe it will contribute to their learning. After all, they have had other engineering classes and they are all packed with information, slides, and equations. How could this style be useful to their learning and remembering? After they play, learn, engage, get feedback, and work with their partners, they are mostly surprised that they do remember things, connect things and can talk about things in a connected and informed way. These two groups with slight variation put their thoughts in colorful and descriptive ways in their last reflections. Eventually, they own what they know and are willing to share and participate.

The calculus-based EM students are traditionally electrical engineers who are required to take the EM course for credit. They experience the process of reflection differently. They are in a class that does not demand them to know and memorize equations, formulations, nor difficult mathematical constructs. They start questioning the validity of the class, since the class does not seem to constantly throw streams of formulations and equations and new material at them. The class shows them the basics, discusses the needs, and engages them in series of connected in-class activities to help them practice and place the knowledge they gain in overall perspective to their past classes and future endeavours. They also are asked to (and eventually show) connect the material to other classes in their reflections and in class activities. They remember the class as an actively engaging class, they had fun learning with their friends, were challenged, and surprisingly remember many of the activities and the concepts that kept repeating and building on each other. They also reflect that they may forget things but are convinced that they can go back and re-walk the process and relearn it.

An important finding of this work, is that students in both the courses learn the content and actively reflect on their learnings. However, the the students in the calculus-based EM class tend to have a better understanding of the overall material and concepts. One might find that the discussion a non-calculus EM student brings is far more deep but the EM students also bring insights, visualization, and better overall connection to application due to the better understanding of the mathematical concepts. The intention of this study was to see how would the students in the traditional classes do, when the material is provided with them in a new format. The results show that the students learn well, understand the connections concepts and the activities. The reflective practice do help them have a more overall connected/integrated knowledge. We see that students in both the courses reflect on the fact that they remember many
interrelated concepts and applications (with different thematics approaches between classes) at the end of the term.

Conclusions
Reflective practices become meaningful experiences for both set of students and are a welcome addition to both courses. The results of teamwork, discussions, and reflections have shown successful learning, questioning, inquiring, and helped students to have better sense making in their journeys of learning and experience in EM. Over the course of the semester, the non-calculus EM students begin to enjoy the process of learning via reflections and are asking deeper questions to learn more about EM. Meanwhile, the calculus-based students aren’t behind and we see that by introducing the process of reflection in the calculus-based course students are becoming better connected learners and thinkers.

There are several distinctions that may be made between the learning styles of calculus-based and non-calculus EM students. Calculus-based EM students could verbalize basic concepts, used equations and were focused on fine details. Non-calculus EM students also showed deep thoughts and depth of understanding of fundamental concepts. Not many students used equations. While each set of students have their own strengths, it seemed that the verbalization, connectivity and depth of non-calculus EM students started to be much better than the calculus-based students but at the end with the new method while students in the calculus-based class show better understanding the non-calculus student are also doing well.

As reflective practitioners we realize that the way we define and instruct may lay the foundation for the student’s knowledge base. However, the student’s real learning is in the story they can personalize and tell others. Therefore our success is defined by enrichment of their stories, creating deeper connections in their minds by relatable experiences and creating an inclusive space for them to share their thoughts.

Future directions
The main finding from our research was that by the end of the semester, students from both the courses were able to reflect, reason and personalize their learning. We observed that students from the non-calculus EM course were far more eager to find and learn more of the course material despite limited familiarity with complicated equations. The calculus-based EM students in the new format do eventually show more in depth engagements with the concepts of the class. They do show good understanding and many do show more passion for the class and the subject. In stage III these students do good communication and capabilities with the material. However, while their knowledge retention and understanding is improved, their passion and excitement for the material is not at par with the other class. This is only seen if one would see the texture of the final weeks of both classes.
This has led us to believe that we can really make a difference in students engagements and understanding, with pre-conditioning of ideas in prior years or in an additional courses where they can spend time thinking, connecting and dreaming about the content, without solely focusing in the mathematical rigor. It is hoped that through the process of reflection they will gain a new appreciation for the course material and be willing to take risks and explore the details of electromagnetism via a mathematical perspective, and even have more in depth understanding of the mathematical perspectives. Finally, in our next iteration we will tune our research questions to better represent the essence of reflection in undergraduate electromagnetism courses.

Acknowledgements
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References
[6]. Anderson, Norman and Mani Mina. “A New Framework for Teaching Electromagnetism: How to Teach EM to all levels from Freshman to Advanced Level Students”, 8.82.1-8.82.17, 2003 ASEE Annual Conference & Exposition Proceedings


[20]. Mani Mina “Dewey and Engineering Education,” in Philosophical and Educational Perspectives on Engineering and Technological Literacy, III” 2016. Published by Technological and Engineering Literacy and Philosophy of Engineering (TELPhE), Division of American society of Engineering Education.

[21]. M. Mina and I. Omidavar “The Relevance and Significance of Deweyan pragmatism for Engineering Education”, in Philosophical and Educational Perspectives on Engineering and Technological Literacy, II” 2015. Published by Technological and Engineering Literacy and Philosophy of Engineering (TELPhE), Division of American society of Engineering Education.


[33]. Reflection Resources: [http://www.ed.ac.uk/edinburgh-award/reflection](http://www.ed.ac.uk/edinburgh-award/reflection)