BYOE: Improving Experience with a Metal Detector Project for Electromagnetics

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I. Introduction

Students in a theory-oriented first undergrad electrical engineering course on electromagnetics (EMAG) often find key concepts difficult to grasp, despite background in the relevant general physics. For example, ideas of the electric field, magnetic field and time-varying induction remain vague to inexperienced students without visual illustrations [1] and tangible examples of the role they play in modern technology. Students at this stage need and expect to be motivated by a more active and applied approach to EMAG than has been traditionally offered [2]-[4]. A typical EMAG text emphasizes the mathematical theory of Maxwell's equations for solving problems [5], [6]. While the mathematical approach excels in expressing relationships of EMAG concisely, and lends tools for effective problem solving, treating the subject solely in this way can leave the practical application context of problems unclear to students. Showing graphic images and videos at the beginning of a class period helps students see the "bigger picture" of typical EMAG applications that support learning objectives. Additionally, assigning concept questions [7] during a class period better engages students via the peer instruction activities of group discussion and polling for self-assessment to sharpen their understanding of the key ideas. However, when EMAG is offered as a non-lab theory-oriented course as it traditionally has been, assigning a single hands-on semester-long project [8] captures students' attention more completely by involving their tactile senses and focusing on a specific application. A suitable course-project also offers ample opportunity for construction, testing, experimentation, and creative modification. As a work-in-progress, this paper presents results of a metal detector project adapted from [9] as a one-semester course activity for EMAG employed at Messiah College during Fall 2018 and discusses some ideas for improving the educational experience.

The search for a suitable course project for this non-lab undergrad first course on EMAG centered on some key criteria related to pedagogical benefit and practicality, so that it could:

1. Clearly illustrate one or more key concepts of the EMAG subject material addressed
2. Involve experimental measurements with available equipment for comparison with the predictions of a theoretical model leading to conclusive results
3. Allow opportunities for creative modification and/or alternative design
4. Be constructed with available low-cost components and materials
5. Connect with subject material of other core electrical engineering courses

Of these five criteria, the first three help support learning objectives of EMAG, and the fourth enables it to stay within a reasonable budget for a non-lab course; the second and third criteria also help satisfy a student clientele including both upper-class engineering and physics majors. The engineering majors typically want a course to provide opportunities for and insights on designing practical applications, while the physics majors, although they don't mind the practical orientation, like to practice the scientific method. The fifth criterion serves to illustrate the integrated interdisciplinary nature of technology, realistically cutting across traditional academic “course” boundaries. The author has been actively seeking projects that meet all these criteria.

Besides the metal detector, several other interesting projects have been tried by others for illustrating concepts of electromagnetics: a capacitive weight sensor [3], a capacitive rain gauge, an electric field probe, a non-contact AC current meter [4] and an electromagnetic crane [10]. While the metal detector project as an example of project-based learning has been suggested, along with others, the literature lacks examples of detailed educational experience in the area of electromagnetics, a void that this author is attempting to help fill with the contribution of this paper. The author has found the capacitive rain gauge and many other open-ended design and construction projects with low cost materials prove difficult to quality-control, leading to inclusive, unsatisfactory results by students of EMAG.

However, the Inductive Metal Detector (IMD) project employed and presented here (see circuit diagram in Figure 1 below adapted from [9]) meets all five of the above criteria.

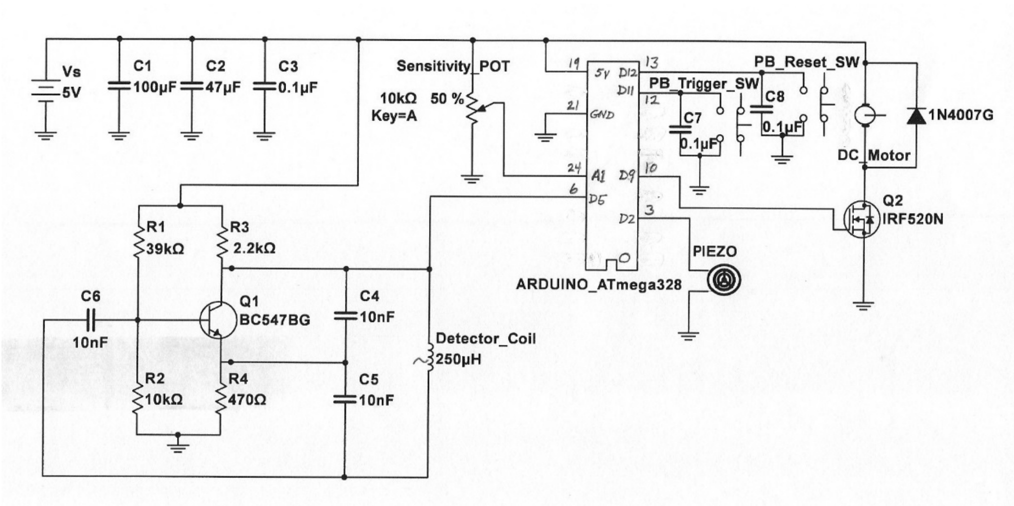

Figure 1. Multisim schematic of circuitry adapted from [9] for this IMD project

Besides the wire-wound coil illustrating the role of the magnetic field as a part of the detector, when present as an inductive element in an oscillator circuit, time-varying magnetic fields of the coil can induce eddy currents in detected metal objects. Since magnetic fields and time-varying induction are key concepts of the EMAG course, this satisfies criterion #1 above. According to procedure, students wound the IMD coil of known wire gauge on a plastic “fishing-line” reel, with the ends of its magnet wire stripped, and measured its inductance using a standard LRC meter. They compared the measured inductance with the predicted value for an ideal solenoid model, versus an improved model that accounts for multiple layers of the wire, to see which matched best. Since design of the baseline IMD prototype has the unexpected behavior of detecting either upshifted or downshifted oscillator frequencies, students were instructed to test various metal objects, including commercial toroid cores, to find objects that shift the frequency, which way it shifts, and why. Students were to propose a hypothesis that correctly accounts for whether the eddy currents or the permeability of the object detected are the predominant factor to explain the result. These two experimental aspects of the IMD project fulfill the science criterion (#2). To satisfy criterion #3, students were required to build a creative modification of the baseline IMD prototype (e.g., to increase its sensitivity for a specified application, or improve its user interface, etc.), or to design and construct an alternative that accomplishes the same objective (i.e., metal detection), with its performance compared against the baseline prototype. Besides the Arduino Starter Kits (available at our library as a loaner), other components and materials were acquired at low cost, satisfying criterion #4. The IMD prototype includes embedded systems (Arduino sketch and hardware circuitry), analog devices / communications circuits (Colpitts oscillator--BJT amplifier circuitry and FET switching of motor vibrator), and basic circuits (potentiometer voltage divider control of sensitivity) to satisfy criterion #5.

Having established background on the course context including need and rationale for selection of the IMD project in this Introduction (section I), subsequent parts of this paper will elaborate on: II) Methods of embedding the project in the course, such as scheduling of the assignment milestones, procedure for construction and experimentation, and assessment of student work; III) Results of student work on the project, including graded assessment and student satisfaction; and IV) Discussion and Conclusions about this work in progress with ideas for future efforts.

II. Methods

The Fall 2018 course syllabus for EMAG at Messiah College introduced students to the IMD project at the beginning of the semester, with details on Canvas, our Learning Management System, and deadlines established in the course schedule. A syllabus statement designated *Group Lab/Project* served as an overview of this project worth 20% of students' course grade:

> For the group project, students will construct and experiment with a given metal detector prototype version (see Canvas for details) by working collaboratively with group members. Students will also develop a creative extension such as a modified or alternative design and compare it with the given prototype version. The report should clearly document results of experimentation with answers to instructor's directed questions, draw appropriate conclusions, detail design of the creative extension, and cite/credit relevant sources from the literature.

A subsequent syllabus prompt *Report on the Group Project* summarized the reporting and oral presentation requirements, beginning with the initial milestone of a three- to four-page proposal/preliminary report (PR). The 14 students in the class were asked to gather themselves into four groups of three or four students each for project work. Each group was required to submit one PR at the end of the 10^{th} week of a 15-week semester, as a rough draft before the final report (FR). The PR consisted of the first four sections of the FR, A) Problem Definition-5%, B) Brainstorming Alternatives-5%, C) Proposed Design-10%, and D) Construction & Test Procedures-10%. The syllabus briefly defined expectations for each section and referred students to website references for more information about the initial IMD prototype. Students were then directed to visit Canvas for a detailed procedure of construction and experimentation, including a rubric with evaluation criteria. The PR submitted by each project group was reviewed by the instructor, assigned a tentative in-progress grade based on rubric criteria. Reviewed drafts of the PR were returned to the students a few weeks before the final due date with comments on how to improve those parts. This gave students ample time to revise their PR, complete their project work, and submit their FR before the end of the semester.

The final report (FR), due on the last regular class period of the semester, consisted of the initial four now-revised parts of the PR above (worth 30%), and the final four parts (worth 50%), completed after finishing the project work. The remaining parts of the FR included sections on E) Electromagnetic Theory-15%, F) Results-20%, G) Discussion and Conclusions-10% and H) References-5%. Oral Presentation (I) and Report Quality (J) were also weighted at 10% each. As with the PR, the syllabus defined expectations for each part of the FR, with detailed criteria in the rubric correlated to each section. During the last class period, each group gave a five- to ten-minute presentation and demo of their creative modification or alternative, to satisfy their project requirements. The outcomes of these results will be reported in the next section of this paper.

To guide students on construction and experimentation, the instructor provided a *Procedure and Questions for the Metal Detector Project* document posted via Canvas at the start of the semester. This procedure 1) detailed steps to construct the "baseline" prototype version of the IMD, including detector coil, Arduino Starter Kit (ASK) and other essential circuitry, and 2) defined experiments with certain questions to answer in the report on issues described in the Introduction section of this paper, e.g., related to the coil inductance and the audible frequency shift, whether up or down from the reference. To identify student expectations, the summary below indicates the objective headings for each step of the procedure, followed by an abbreviated description of how they were to complete that step.

1. *Build the hardware circuitry of the metal detector.*

Each student group used one Arduino Starter Kit (ASK) provided on loan from the library. Most components they needed were already in the ASK. However, they also wound their own detector coil around a given plastic reel using 24 AWG magnet wire from a spool provided. Students acquired from the department electrical supply certain specified resistors, capacitors and a transistor (BC547 in Colpitts Oscillator circuit of Figure 1) not in the ASK. They used the 5-volt supply available with the ATmega328 of the ASK connected with a USB cable to a PC.

2. *Verify your oscillator works.*

Students tested the Colpitts Oscillator part of their IMD circuit to ensure it was wired and functioning properly at the expected frequency well above the audio range. To do this they used the display and frequency counter of a Tektronix TDS 2012 oscilloscope (scope).

3. *Measure and record your oscillator frequency.*

With the TDS scope as above, students measured and recorded the actual unaffected resonance frequency (f_r) of the Colpitts Oscillator circuit (keeping the coil well away from any metal object) using the specified capacitors and a detector coil consisting of 50 turns of 24 AWG magnet wire wound on a reel with a 5.1 cm diameter and a width of 1.3 cm.

4. *Measure and record the inductance of your detector coil.*

Students temporarily disconnected the leads of their detector coil from the circuit breadboard and plugged its leads into a BK Precision LCR meter (Model 879). With the LCR meter set at its highest frequency setting (10 kHz), students recorded the inductance (L) in micro-Henry (μH).

5. *Calculate and record the predicted inductance of your detector coil.*

Students first calculated the predicted inductance of the coil using the formula for a simple solenoid model (SSM) derived in a typical electromagnetics text [5] based on the number of turns (N), coil radius (r), wound coil length (h) and the permeability of air (μ_0). They compared the percentage error of this SSM prediction versus the measured value in step 4 above and explained the discrepancy. Next, they predicted the inductance (L) with a Multilayer, Multirow Coil Model (MMCM), using an online calculator [11] (see Fig. 2 below), and observed whether it made a better prediction of the inductance than the SSM, explaining in their report why or why not.

$$L = \frac{0.8\,(\text{Radius}^2 \times \text{Turns}^2)}{6\,\text{Radius} + 9\,\text{Length} + 10\,\text{Depth}}$$

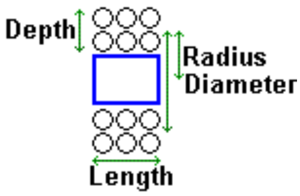

Figure 2. Inductance formula and coil dimension for the MMCM from [9]

6. *Calculate the predicted frequency of your Colpitts Oscillator.*

Students measured the key capacitances of the Colpitts Oscillator circuit along with the measured value of the coil inductance (L) from step 4 to calculate the predicted resonance frequency $f_r = 1/(2\pi\sqrt{(LC_T)})$ [12] and compared it to the measured value.

7. *Upload the Arduino Sketch for the Metal Detector Project.*

Students downloaded the Arduino IDE to their laptop or computer that members of the group intended to use for this project. They then imported the Arduino metal detector sketch from a link in Canvas as a file/folder to their Arduino IDE. After compiling and verifying the Arduino sketch (code) they uploaded it to their ASK using a USB cable provided.

8. *Verify the functionality of your Metal Detector.*

At this stage, students tested the functionality of the IMD by pressing the reset and trigger buttons (Figure 1) to see if a fluttering audio sound was emitted from the piezo speaker. If not, they did some troubleshooting of the circuit and/or sought help from the instructor. Once the fluttering audio reference tone of the IMD was established, they checked various detectable metal objects with the trigger button depressed, to hear the shift in audible frequency. When functioning properly, if the detectable metal object was close to the detector coil and/or large enough to exceed the threshold established by the sensitivity POT, the DC motor would spin, acting as a tactile vibration indicator to supplement the audible indication of frequency shift.

9. *Experimenting with your Metal Detector.*

Students tried detecting different given objects including metal disks, solid metal slabs, a spring, toroid cores, and other pieces of metal they had available. After these observations, they were to answer the questions, "Which metal objects produced a response as indicated by the audible frequency and/or also the spin/vibration of the motor? Which ones did not? Why? For detectable objects, did the audible signal shift up or down in frequency from its unaffected level? Why?" The students were given some hints to help answer the last question here based on the expected effect of increased permeability and/or eddy currents induced in a metal object together with Faradays and Lenz's Law. Students were to construct a table of their results with the metal detector, at a fixed sensitivity, including the identity and size of the objects they tested, and then answer the questions, "What can you conclude from this about the spatial sensitivity of your metal detector? How in your design could you increase the sensitivity of your detector?"

10. *Alternative Detector Coil.*

Students were to change the design of their detector coil (e.g., wind a new one) to increase its sensitivity, and then repeat steps 3-6 with their new coil. They were then to record the new results for their report and explain them.

11. *Creative Alternative or Creative Extension version.*

Students referred to Canvas and/or the course syllabus for ideas to consider, and expectations for the report. This was to be a very open-ended part of the project with no prescribed procedure.

Besides the reporting prompts and stepwise procedure for the IMD project described in this section of the paper, students were given three full 50-minute class periods during the semester to make progress on their project work, while the instructor was directly available to assist and answer questions. The rest of the work project groups did outside of class based on the initiative of individual students and availability of group members to meet. The next section of this paper will present results of the IMD project including group outcomes, report assessment and student satisfaction.

III. Results

The results presented in this section focus on student outcomes of key experiments related to the IMD project, rubric assessment of their final reports, response to their satisfaction survey questions, and the products of their design in the form of creative modification or alternatives.

Table 1 below shows the group results of both measurements and calculations for the initial detector coil inductance. The initial detector coil was specified as 50 turns of 24 AWG magnet wire on the same plastic spool that all groups had in common. Inductance measurements were made with a BK Precision LCR meter (Model 879). Calculations of the inductance were made with a Simple Solenoid Model (SSM) and a Multilayer, Multi-row Coil Model (MMCM). Percentage error was calculated as %Error = [|(measured — predicted)|/measured]x100%.

Table 1. Measurements and calculations: initial detector coil and associated dimensions

	Measurements				Calculations			
Group #	Inductance L (μH)	Length h (cm)	Radius r (cm)	Depth d (cm)	SSM L (μH)	% Error	MMCM	% Error
1	207	1.3	2.75	0.1532	574	177	200	3.4
2	201	1.27	2.54	?*	501	150	68.5**	N/A
3	210	1.5	2.6	?*	445	112	182	13
4	208	24**	?*	?*	120*	N/A	52**	N/A

(*not reported; **calculation or measurement error; N/A-not applicable, erroneous result)

Table 2 below shows the results of both measurements and calculations of the Colpitts Oscillator frequency using the reference formula [12]. The oscillator frequency was measured with the Tektronix TDS 2010 scope, and the capacitances with a standard digital multi-meter.

Table 2. Measurements and calculations: Colpitts Oscillator frequency and circuit components

	Measurements				Calculations	
Group #	Frequency f_r (kHz)	Capacitance C_1 (nF)	C_2 (nF)	Inductance L (μH)	Frequency f_r (kHz)	% Error
1	153.6	11	9.6	207	154.4	0.52
2	165	10	10.7	201	156	5.4
3	159	10.1	9.77	210	155	2.5
4	158.2	?*	?*	208	2.57**	N/A

(*not reported; **calculation or measurement error; N/A-not applicable, erroneous result)

Table 3 below shows results of rubric assessment for the IMD project including a breakdown for each section of the final report, with non-report sections such as the oral presentation, overall quality of the written report and total accumulated points by each group.

Table 3. Parts and composite results of rubric assessment for the IMD project (see Methods section of this paper for identity of each report section and other graded components)

	Preliminary & Final Report Sections				Final Report Sections, Oral Presentation Component, Overall Quality of Report Component and Totals						
Group #	A	B	C	D	E	F	G	H	I	J	Total
Max Possible	*5*	*5*	*10*	*10*	*15*	*20*	*10*	*5*	*10*	*10*	*100*
1	5	5	9	10	12.9	17.6	9.2	4	10	10	92.7
2	4.5	4.5	9.6	9	14.1	18	9	5	10	10	93.7
3	5	4.5	8	9	15	16	10	3	10	7	87.5
4	4.6	4.9	9	9	9	14	8	3	10	9	80.5
Overall Average	4.8	4.7	8.9	9.2	12.8	16.4	9	3.8	10	9	88.6

Table 4 below shows results of 14 students' ratings given anonymously on 3 survey questions related to their personal experience on doing the Inductive Metal Detector (IMD) project in the EMAG course. The ratings are based upon a Likert type scale with the distribution: 1=strongly disagree, 2=somewhat disagree, 3=undecided, 4=somewhat agree, and 5=strongly agree.

Table 4. Likert Scale ratings by 14 EMAG students on their experience with the IMD project

Survey Questions	Average Rating
1. I enjoyed the experience of doing the IMD project in this course.	3.8+/-0.6
2. I learned something from doing the IMD project in this course.	4.1+/-0.5
3. The IMD project involved a satisfactory amount of creative design [...]	4.3+/-0.5

Table 5 below shows the 4 additional open-ended survey questions (4-7) given to the same 14 students regarding their personal experience with doing the IMD project in the EMAG course, and how many students responded to each question.

Table 5. Open-ended survey questions on students' IMD project experience with # of responses

Open Ended Survey Questions	Total # of responses
4. The IMD project could be improved by…	14
5. Something I learned from doing the IMD project in this course is…	14
6. Something I enjoyed or did not enjoy about doing the IMD project is...	13
7. Other comments or suggestions I have are…	8

The open-ended survey questions in Table 4 elicited a wide variety of responses from the 14 students in this Fall 2018 EMAG class. Their most common responses to Q#4 was a suggestion along the lines of "providing more guidance on the creativity to be put into the alternative design" (6) or a "less complicated circuit" (2). Seven other suggestions were made by one student each. The most frequent responses to Q#5 were related to "how a metal detector works" (3) or "understanding the Arduino and/or its language" (2) or "how metal and permeability affect inductance" (2). Sixteen other comments were made by one student each. In response to Q#6, several students said something about "not enjoying [or struggling with] putting together the circuitry", or "troubleshooting it", or "lack of knowledge about it" (4), while others said they "enjoyed building the circuitry of the detector, despite it being somewhat challenging" (2), and still others said they enjoyed "brainstorming and testing" or "comparing alternative designs" (2). Eight other comments were made by one student each. Finally, in response to Q#7, the most common responses were that the final report should be due closer to the preliminary report (2) and that the Arduino bread boards were (almost) too small, so larger breadboards were needed (2). Seven other comments were made by one student each.

Products of student design were quite varied, taking the form of two creative modifications on the given IMD prototype, and two alternative approaches. Table 6 below describes for each group the creative modification or alternative approach they chose to develop.

Table 6. Creative metal detector product outcomes for each group

Group #	Description of creative modification or alternative design
1	"Rover" handheld version of IMD in a Lego framework w/LED indicator
2	Simplified IMD circuit alternative designed around a 555 Timer
3	LCD display modification of IMD w/messages to improve user interface
4	Pulse induction metal detector alternative for short range security use

Having presented in this section the outcomes of key experimental results, graded assessment, student satisfaction survey responses and creative designs, the next section will comment on these results, draw some conclusions and address opportunities for future work.

IV. Discussion and Conclusions

This section discusses some questions this work raises, reflects upon and draws conclusions about the outcomes and suggests ideas for future work, as related to the IMD project employed in an EMAG course at Messiah College during the Fall 2018 semester, and for the broader engineering education community. Project outcomes discussed here include key experimental results, graded assessment, responses of the student satisfaction survey and creative designs.

Questions raised by this work include best learning strategies and concept clarity in EMAG, as well as metal detector applications in professional practice. Problem- or project-based learning (PBL) has become popular in education at large [13], and in several disciplines of engineering education [14]-[16] but documented detailed examples of PBL for EMAG have been scarce, and thus best practices unclear. Guidelines for PBL [14] have been generally followed in this work, though students have been given a baseline prototype to build prior to pursuing creative modifications to ensure certain key concepts have been addressed. The author has used the Electromagnetics Concept Inventory (EMCI) [17] for several years as a pre- and post-test to assess student learning as a result of various active learning strategies, besides the IMD as a PBL example reported here. The EMAG course at Messiah College addresses 15 out of the 25 concept items presented by the EMCI (Fields and Waves version), yet only 2 EMCI items involve Faraday's Law of induction, a key concept of the IMD project. Thus, a more customized concept inventory that includes key concepts of the IMD project (such as mentioned below) may be more effective for this EMAG course. While employing the IMD as PBL in this EMAG course was primarily intended to stimulate student enthusiasm and awareness of connections between theory and hands-on practice, in their report on the project, students were also expected to provide background on a typical application in the Problem Definition section, based on their own research. Besides treasure hunting, security in public places is perhaps the most common and important application. With enough research, students should find that due to tradeoffs on extent of penetration (deeper at low frequency) and size of detectable metal object (smaller at high frequency), rather than one typical frequency being use for security, in professional practice, a whole range of frequencies (e.g., 3-100 KHz) may be used to get best results [18].

Regarding outcomes of the IMD project work itself, one key experimental result, the detector coil inductance, as reported in Results Table 1, shows how well most groups did with measurements, but not always so well with calculations. Direct measurements of the coil inductance by each group were reasonably accurate and within the expected range for the given specifications of the IMD prototype. However, calculations of the predicted value based on the Simple Solenoid Model (SSM) and the Multilayer, Multi-row Coil Model (MMCM) were not all so satisfactory. Group 1 evidently was "on the ball" with a calculation of the inductance by the MMCM very close to the measured value (< 5% error), including reasonable recorded values for each of the three critical parameters. Group 3 also obtained a fairly close calculated result but failed to record a value for the depth parameter, casting doubt on the validity of their result. The other two groups did not measure or record the critical parameters of the coil on which the MMCM prediction depends. Thus, they completely missed the point about the better prediction a valid coil model (such as MMCM) makes. The instructor may need to intervene to ensure students have made the necessary coil measurements, and/or spend class time specifically addressing the comparison between SSM versus MMCM. Physics majors in the class (who all happened to be in Group 1) evidently did better on this work than the engineering majors in the class. The engineering majors may need to be more convinced that predictions of a valid model yields benefits for answering "what if" questions of design work. To address these deficiencies, the instructor may develop concept questions related to coil configuration (e.g., For a short coil, are fringing effects at the ends negligible? If not, would the inductance be over or under-predicted?) and a well-crafted problem-oriented project question (e.g., if you were to redesign the oscillator frequency at 140 kHz, how many turns of the detector coil would you need?).

The other key experimental result, the oscillator frequency reported in Results Table 2, was better handled overall by most groups. Direct measurements of the frequency by all groups was in the expected range for the inductance of the previous part, and the Colpitts Oscillator circuit components specified. Calculations of the expected frequency [12] depends on the coil inductance (L) and the capacitances C4 and C5 (Fig. 1) in the Colpitts Oscillator circuit. Three out of four of the groups obtained a predicted frequency reasonably close (< 6% error) to the measured value. The other group either misread the schematic or misinterpreted the oscillator frequency formula. The instructor may need to go over the circuit schematic next time more carefully, to make sure all students understand how the oscillator frequency formula applies.

The graded assessment components reported in Results Table 3 show total scores ranged from a low of 80.5% to a high of 93.7%, reasonable for an undergraduate upper-class required course. All groups did well (≥ 90%) with the revised parts of the Final Report (sections A-D), since they were able to resubmit the first Preliminary Report draft with improvements based on comments by the instructor. Where some groups struggled the most was on the most heavily weighted sections Electromagnetic Theory (E) and Results (F). The reason for their difficulties included misreading the circuit schematic as above, miscalculations, mis-measuring critical parameters, and/or misunderstanding the theory of coil models. Also, some groups had trouble correctly explaining why the oscillator frequency would shift up or down, when the detector coil was near a highly permeable object versus a conductive object with eddy currents. A concept question that distinguishes between these effects and why they oppose each other may be helpful. Other errors in report writing mostly involved issues outside the scope of the EMAG course.

Rated responses to the student satisfaction survey questions reported in Results Table 4 indicate how the students reacted overall to the project. Responses by students based on their experience with the IMD project showed they *Somewhat Agreed* that 1) they enjoyed it (3.8/5), 2) they learned something from doing it (4.1/5), and 3) it involved a satisfactory amount of creative design opportunity (4.3/5). While the latter of these might be considered satisfactory enough for a work in progress, making some adjustments to the IMD project based on specific open-ended student comments might help raise these ratings to a higher more ideal level.

Responses to the open-ended student satisfaction survey questions listed in Results Table 5 reveal more specifics about the student reaction from their experience. Since six students said something to the effect that they felt the IMD project could be improved by more guidance on the creativity to be put into the alternative design, the instructor may consider taking a less open-ended approach to the design aspect in the future. Possibilities include a more specific client/problem definition to target, or a metal detector competition challenge at the end of the semester. Since a couple said a less complex circuit would be better, it would be interesting to find out if students' attitude about complexity would change if competition were involved.

While the responses by more than one student to "something I learned from doing the IMD project in this course is…" including "how a metal detector works" and "understanding the Arduino and/or its language" and "how metal and permeability affect inductance" represent worthwhile outcomes, the instructor may need to formulate more specific learning objectives for the project to prioritize them. Responses to "something I enjoyed or did not enjoy about the IMD project was…" revealed some reasons for their mixed reaction: while a couple students said they "enjoyed building the somewhat challenging detector circuitry", and a couple other said they enjoyed "brainstorming and testing" or "comparing alternative designs", several other students said they did not enjoy "putting together the circuitry", or "troubleshooting", or their "lack of knowledge about it." Even though the instructor did not consider much circuit knowledge necessary to do the project, the limited experience of some non-electrical students evidently undermined their confidence. To address this concern, the instructor may offer simpler and more complex circuit version options for the IMD project, for student groups to self-select their level of challenge. One approach that has been suggested would be to start with the RLC by itself and examine its step response on the oscilloscope when driven by a square wave. This way students could evaluate alternative coil designs more easily and directly, including wire gauge and Q-factor. Then they could proceed to investigate a more reliable detection method Furthermore, it may help to oversee group formation to ensure each group includes at least one electrical engineer. A couple students suggested moving the due date of the Final Report closer to that of the Preliminary Report and using a breadboard larger than the Arduino Starter Kit has.

The creative metal detector product outcomes identified in Results Table 6 show the variety of directions student groups went to fulfill this requirement. Although the approaches typically involved knowledge outside the scope of the EMAG course, the instructor considered the variety a bonus as it built upon the objective of connecting with other course material, and made for more interesting oral presentations by groups to the rest of the class at the end of the semester.

To recap, this paper has addressed an IMD project largely motivated by the need in an EMAG course to capture students' attention in a practical creative hands-on way, and to illustrate concepts such as the magnetic field and induction which would otherwise remain abstract. In the interest of continuous improvement, an ABET best practice, both student assessment and feedback has been carefully reviewed, along with references in the literature as available, to identify best steps forward. The outcome of this first attempt with the IMD as PBL for an EMAG course seems satisfactory but leaves some room for improvement. Ideas for future work summarized from the discussion above include: 1) intervention by the instructor at more key milestones in the project work to ensure critical parameters have been measured and recorded by each group, 2) building more "bridges" to project work in the course by addressing key concepts and models specifically during class time, 3) introducing a specific client/problem definition to target project work and/or a competition challenge at the end of the semester to increase student motivation with optional versions of the project for students to self-select their level of challenge, and 4) some other minor adjustments such as streamlining procedure and report requirements, adjusting due dates, structuring group formation and providing a larger breadboard for circuit construction. The author welcomes any further feedback or suggestions from the ASEE community on this experience of employing the IMD project, and hopes this work helps stimulate ideas for more projects in EMAG or other courses at other institutions, to develop a more complete database of experiences toward best practices of project-based learning.

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