The Well of Maxwell

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***Abstract*—We present a system that aims to teach students the fundamental laws of electromagnetism through an interactive booth housing two circuit demonstrations for Faraday's law of induction and Ampere-Maxwell's law, and a web application interface that presents animations of the electric and magnetic fields corresponding to the state of the experiments, and related educational content with gamified components. An ADALM transmits the relevant data from the circuits to the web application to make necessary updates. The highly integrated system would be more conducive to learning than textbooks, videos, or experiments alone.**

***Index Terms*—ADALM, Ampere-Maxwell's Law, Django, Education, Electromagnetism, Experiments, Faraday's Law, Maxwell's Equations, Web Application**

I. Introduction

Electromagnetism is an important branch of physics that is fundamental to many aspects of modern society, such as electrical engineering, information technology, and computers. At the same time, E&M is also a fascinating field, because it describes fundamental laws of nature. However, many students struggle in E&M courses because the subject is abstract, non-intuitive, and difficult [1]. Indeed, analyzing invisible physical quantities that vary in both space and time, such as electric and magnetic fields, can be challenging for people. Textbooks provide detailed descriptions of E&M phenomena, but these descriptions are non-interactive. On the other hand, E&M experiments can demonstrate key principles, but oftentimes people only focus on the effects that they can observe and neglect the underlying causes and effects.

In addition to traditional textbooks and experiments, online educational videos on platforms such as YouTube and Khan Academy have recently become another popular tool that students use to learn E&M concepts. These videos often incorporate animations of physical phenomena and explanations. However, seeing the experiments is still not as effective for learning as doing the experiment.

Therefore, we want to design a system that integrates interactive E&M experiments and intuitive analyses of E&M concepts. More specifically, we want to teach students the fundamental laws of E&M in a fun, visual and effective way, and provide them with intuition and inspiration for further study through two circuit demonstrations and a web application interface that presents education modules with gamified components. Hence the name "The Well of Maxwell."

The intended users primarily are students in elementary school to those in college, but anyone interested in hands-on experiments and physics can use our system. Therefore, to reach such a broad range of users, we will tailor the educational modules in the web application towards people with different levels of prior knowledge in E&M.

II. Use-Case Requirements

In order to teach students Maxwell's equations in an engaging and effective way, the overall system needs to ensure an interactive, instructive, and safe user experience.

To provide an engaging user experience, the hands-on experiments and interactive games built into the web application should achieve an average rating of 4.5/5 in "fun" when surveying users after using the device, as other commonly used educational resources have at least 80% user satisfaction ratings (such as Khan Academy).

Additionally, the device is targeted towards engagement for at least 3-5 minutes, including time spent reading the educational modules, answering questions, and performing the experiments. We believe that 3-5 minutes is a good target, as the modules in the Carnegie Science Center have an average user time of 2-3 minutes based on our observations.

In addition to user engagement, another important use-case requirement is to ensure that the device is instructive. To that end, the content taught through the modules must represent correct electromagnetic theory. Moreover, users with different background knowledge must also be able to benefit from the device. Therefore, we plan to create 3 different sets of modules. The first set is for students with no physics experience; the second is for students with physics experience but no E&M experience; and the third is for students with previous experience with E&M. To provide accurate information, the voltage measurements in Faraday's law experiment displayed on the web application must be within 3% of the voltage measured by a lab grade oscilloscope. As standard voltmeters have an error of between .5% and 1%, we believe this is a reasonable benchmark.

Furthermore, to ensure a smooth learning experience, the product must have a 1-second latency at most between the time the state of an experiment changes, and the time information is displayed on the web application. We believe anything beyond a 1 second latency may cause frustrations when users are learning from the device.

Lastly, to ensure safety and repeatability, there must be a separation between the user interface and experiments, and all components of the device must be functional after 1000 uses, where a "use" is defined as any time the user interacts with the Faraday's law experiment or the Ampere's law experiment. The web application also must be secure against SQL injection, XSS attack, and CSRF attack.

III. Architecture and/or Principle of Operation

From the users' perspective, the basic framework of the system is as follows: the user completes a diagnostic quiz about their knowledge in E&M on the web application via the laptop provided on a table first, and they will be directed to the appropriate educational modules, which are stored in a SQLite database by administrators. After completing the educational modules, they will be given instructions on how to perform each experiment through the web application. While interacting with the experiments, the user can observe the changes in the visual indicators (e.g. LEDs in the Faraday's law experiment, the compass in the Ampere's law experiment).

We now describe the principles of operation for the system, including the Faraday's law experiment, the Ampere's law experiment, the web application, and the hardware-software bridge. As a guide to our discussion, Fig. 1 shows the overall system block diagram, while Fig. 2 shows the annotated complete set-up of the Well of Maxwell.

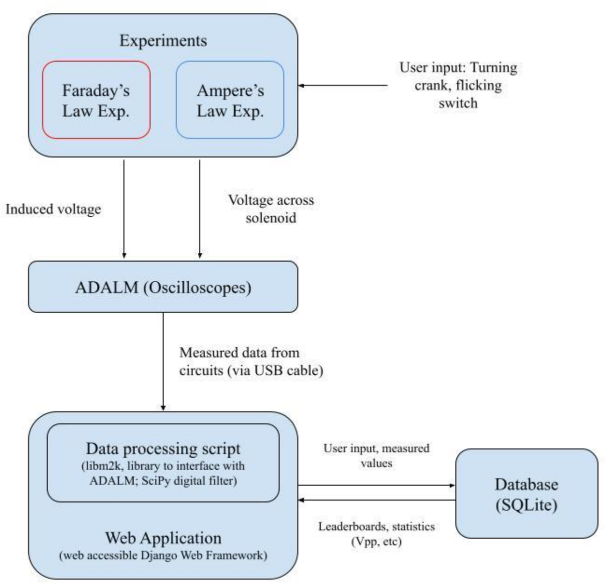

Fig. 1. Overall System Block Diagram.

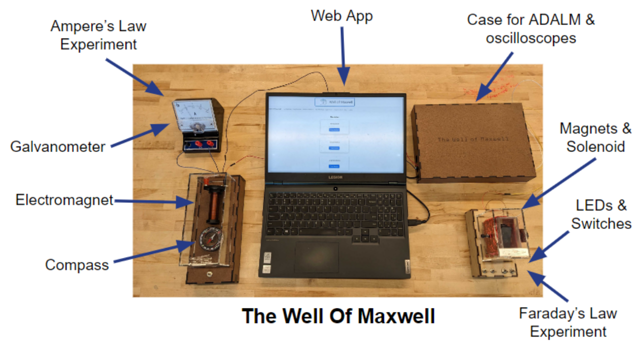

Fig. 2. Complete setup of The Well of Maxwell

A. *Principles of Operation of the Faraday's Law Experiment*

The Faraday's law experiment can be seen in Fig. 3, while a model can be seen in Fig. 4. Faraday's law of induction states that a time varying magnetic flux through a surface induces an EMF at the boundary of the surface. This statement can be summarized by the following equation:

$$EMF = -d\mathbf{\Phi}/dt, \tag{1}$$

where $\mathbf{\Phi}$ is the magnetic flux (Wb). When two magnets housed inside an induction coil are rotated, the poles of the magnets point along different directions, and the magnetic flux through the induction coil changes. The user can then use the induced EMF to turn on LEDs by changing the positions of the switches located on top of the case, as shown in Fig. 3.

The original proposed mechanism for inducing an EMF in the design review was to slide a magnet through an induction coil. However, that design was deemed unviable as not enough EMF was induced to turn on LEDs.

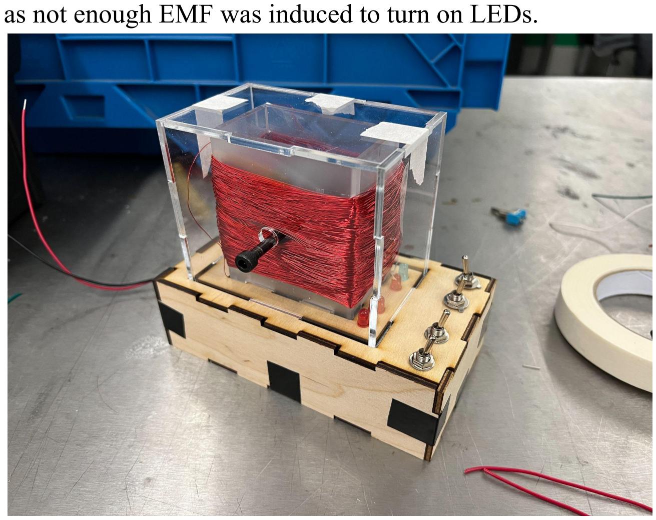

Fig. 3. Faraday's Law Experiment.

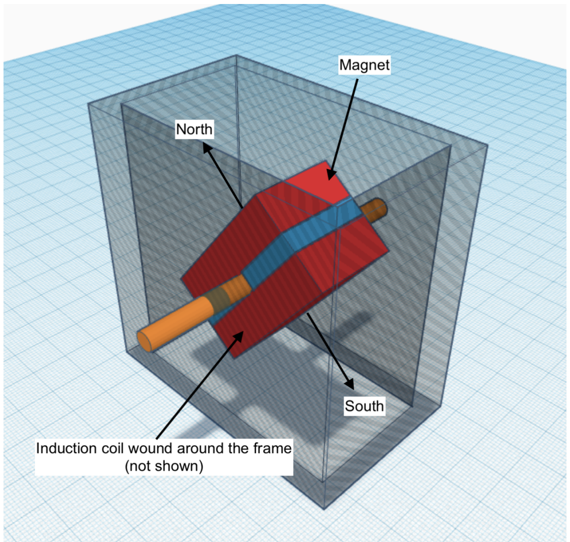

Fig. 4. TinkerCAD Model of the Faraday's Law Experiment.

B. Principles of Operation of the Ampere's Law Experiment

Ampere's law is defined as follows:

$$\oint B \cdot dl = \mu_0 I_{enclosed}, \quad (2)$$

where $B \cdot dl$ is the scalar product of the magnetic field and vector segment of the path, μ_0 is the magnetic permittivity, and I is the net current enclosed by the path.

In essence, this indicates that an electric current or a changing electric flux through a surface produces a circulating magnetic field around any path that bounds that surface. To show how an electric field can lead to the production of a magnetic field, we are recreating to some extent the set-up that Professor Hans Oersted of the University of Copenhagen had when he discovered that wires with flowing current produce a magnetic field. The professor was giving a lecture in 1819 on electric current and magnets. He happened to leave a compass next to a conducting wire, and he later noticed that the current was deflecting the compass.

Our experiment is designed to replicate this discovery by also using a compass and its deflection to show the presence of a magnetic field, as is detailed in the system implementation section. To maximize the visual impact of the experiment, we will need to maximize the deflection of the compass. This will simply be done by orienting the compass in the position that gives the most deflection from its natural direction.

C. Principles of Operation of the Web Application

The web application is built using the Django MVC framework.

From the web application hosted locally on a laptop, a user can view the educational modules, as well as instructions and data from each experiment. There are also interactive exercises in the modules page, and a gamified quiz that users can take and compete for a high score. Since the design review, there have been no major changes in the operation of the web application.

D. Principles of Operation of the Hardware-Software Bridge

An ADALM2000, a portable USB-powered instrumentation tool, is used to measure the induced EMF in the Faraday's law experiment and the voltage across the electromagnet in the Ampere's law experiment from the experiment. The data is sent to the laptop through a USB connection. The values will be updated in real time as the database updates through HTTP requests between the web application and the laptop.

Since the design review, the major change we have made was the use of an ADALM2000 instead of an Arduino MKR that we had initially planned. The exact reason for this switch is detailed in Section V of the report.

IV. Design Requirements

Having considered the use-case requirements that a user would expect from interacting with the booth, we now direct our attention towards the more specific engineering design requirements that need to be met to achieve the use-case requirements.

Providing instructive content and letting people learn effectively is the most important aspect of this project. Therefore, to ensure the correctness of the content on E&M, the content should reference authoritative textbooks, such as University Physics with Modern Physics by Hugh Young and Roger Freedman [2].

For the educational modules to match users' background knowledge, the modules must consider different math and physics concepts that one may or may not be familiar with, such as vectors, vector fields, and calculus.

To ensure the experimental values displayed on the web application do not mislead people, the measured voltage should be within 5% of ADALM oscilloscope measurements.

In addition to providing accurate educational content, the system should also deliver a smooth learning experience by keeping the latency between user input and web application response below 1 second.

The learning experience should also be fun and engaging. To that end, some gamified components should be added to the modules, such as displaying a leaderboard of the highest induced voltages using the Faraday's law experiment on the web application. The educational content should be free of grammatical errors and use complete (but concise) sentences. The fonts should be sans serif (such as Arial), and large enough to increase readability, especially for people with dyslexia. The animations should have at least 30 frames per second, which is the standard frame rate recorded by modern smartphones.

Of course, the most fundamental concern of the project is to ensure the safety of the users. Thus, the circuits should be enclosed in transparent, 1/8" acrylic cases. To ensure the cybersecurity of the web application, all input boxes should be sanitized to avoid XSS attacks. SQL injections should be prevented by verifying user inputs and parameterized queries with prepared statements, never using input directly. Additionally, CSRF tokens should be employed on each form or survey submission to prevent CSRF attacks.

V. Design Trade Studies

The following section identifies the design of each of our subsystems and the trade-offs we made to satisfy our use-case requirements.

A. Faraday's Law Experiment

Because a time varying magnetic flux through a surface induces an EMF at the boundary of the surface, naturally, the design of the Faraday's law experiment hinges upon how to create a magnetic field, how to vary the magnetic flux, and how to manifest the induced EMF.

There were two apparent options to create a magnetic field: using either electromagnets or permanent magnets. Operating an electromagnet requires a constant supply of current to create a substantial magnetic field. On the other hand, permanent magnets are chosen because they are economical, simple, and do not require power to operate.

There are multiple ways to change the magnetic flux through a surface, including moving a conductor in a static magnetic field, varying the magnetic field through a stationary conductor, or combining the two methods.

Using a Faraday disk, which utilizes the first principle to vary the magnetic flux, is considered first because of its relative ease of construction and historical significance, which may attract humanities-inclined students. However, the design is not selected because it is somewhat complicated to explain the underlying induction mechanism as the motion is circular.

Another classic example frequently presented to students is sliding a conducting bar over a pair of fixed rails over a static magnetic field. The experiment can be explained relatively easily, but generating a significant and uniform magnetic field under the circuit is not feasible, thus eliminating the design.

Initially two experiment ideas that use the second principle (varying the magnetic flux through a fixed conductor) are analyzed: A magnet can either be slid through or dropped into an induction coil. Because the experiment needs to be engaging, we plan to use the induced EMF to light up a light emitting diode (LED) to visually show the effect. To do so, the magnetic field must change rapidly enough to induce an emf higher than the turn on voltage of an LED. However, it is difficult to accelerate a magnet quickly by sliding it, so it may not generate the required emf. On the other hand, dropping a magnet can potentially induce the necessary voltage with the help of gravity. However, after experimenting with these two options and measuring the induced EMF with an oscilloscope, we realized that the induced EMF was too small (< 1V) and too transient (<250 ms), which is not high enough to turn on LEDs.

Therefore, a third experiment idea was considered. Instead of relying on linear motion to change the magnetic field, we decided to rotate magnets housed inside a coil of magnet wire, because rotation of the magnet can cause more rapid changes in the magnetic flux. Compared to the other options examined, there are no obvious shortcomings of this approach.

B. Ampere's Law Experiment

As mentioned previously, we are replicating the 1819 experiment that led to the discovery that a flowing current generates a magnetic field in the Ampere's law experiment. One alternative method to display this experiment would be to replace the compass with a neodymium magnet and place it on a slider that allows the magnet to be attracted or repelled based on the direction of current in the solenoid. The reason we did not use the magnet alternative is that the magnet does not move back to a "natural" position when the power supply is cut off, as compared to the compass that moves back to natural north. This natural movement helps emphasize the change brought about by the induced magnetic field.

C. Web Application

There exist many possible trade-offs and design choices in the software and web application.

For designing a web application, it is much easier to use a web framework to host the web application. Currently, competitive web frameworks are Django, Flask, SpringBoot, RubyOnRails, Angular and ViewJS. Since our team is much more comfortable with Python than other programming languages, using a python framework is what we decided on.

Out of these, DJango and Flask are both python frameworks, so the project was chosen to be based in one of these two. Advantages of Python are fast development speed, scalability, and simplicity. Between Django and Flask, Flask provides more flexibility than Django and is also somewhat more intuitive to work with and handles more back end features on its own. Django allows more customization of some backend features, though can be more cumbersome to work with at times and must use a MVC model. However, the key factor in our team's decision to use Django over Flask is that Django projects can use dynamic web pages, which is highly useful both for displaying information in the educational modules, and showing real time animations of the graphs on screen. Django also has better real time response and faster response rate to updating user feedback. Thus, for this project we decided to use Django.

For the Database, competitive databases used in industry are Postgres, MySQL, MonogoDB and DynamoDB. Since we have the most experience with relational databases similar to SQL, our team was choosing between MySQL and SQLite. SQLite provides simplicity, and is a lightweight database that does not require a lot of backend support. However, SQLite cannot support as many entries as MySQL and is slower for larger datasets. Since this product focuses on the user experience and fast display to the user, SQLite is a simple yet efficient database that fits the needs of the web application. Additionally, the product does not require a high number of database entries, and does not require parallel threading or high throughput access, SQLite is more simple to use and more lightweight than MySQL. Thus, SQLite was the design choice.

In terms of the front end, the most common industry choices are Native HTML/ CSS, ViewJS, React, Angular, and Bootstrap. Angular and React require more back end support, while bootstrap is lightweight, and consistent. Thus, for this project we decided to use bootstrap to display the front end animations and display of the web application.

D. Hardware-Software Bridge

We considered using either an Arduino or an ADALM to sense the induced EMF in the Faraday's law experiment and the voltage across the solenoid in the Ampere's law experiment. The table below summarizes the capabilities of each device.

Table I. Comparisons between an ADALM2000 and an Arduino MKR WiFi 1010

	ADALM2000 [3]	Arduino MKR WiFi 1010 [4][5]
Resolution	12 bits	12 bits
Sampling rate:	100 MS/s	10 KS/s
Input range	±25V	0-3.3V/5V
Scope scales	1mV to 10V/div	N/A
Price	$236.25	$38.60

It is clear that the ADALM2000 has a much better sampling rate than the Arduino. The advantages of the Arduino over the ADALM2000 are its smaller form factor and cheaper price. However, for our purpose the footprint of an ADALM2000 is acceptable, and since we already have access to them through other courses, such as 18-100, we do not need to purchase one. An Arduino is also easier to program since it's well-documented. Ultimately, we chose to use an ADALM.

VI. System Implementation

A. Faraday's Law Experiment

Fig. 3 shows the Faraday's law experiment. To induce a motional EMF, the Faraday's law experiment utilizes the rotation of two ceramic magnets housed inside a coil of (24 gauge) magnet wire. The two magnets are hot glued onto a bolt, and a knob is attached to the bolt to make rotating it easier. A coil of wire is wrapped around a laser-cut acrylic frame. Sandpaper was used to expose the conducting material at the two ends of the coil. These two ends are then connected to a half-size breadboard housed inside a laser-cut wood base, underneath the frame for the magnets and induction coil. Another laser-cut acrylic case slightly larger than the frame is placed around the frame to separate the apparatus from the user in order to prevent any possible damages to the equipment.

To demonstrate basic circuit laws, such as the behaviors of circuit components placed in parallel and series, the induced EMF is used to power LEDs. Fig. 5 shows the circuit diagram for the LEDs and switches, while Fig. 6 shows the wiring diagram. Four LEDs, three red and one blue, are attached to the base. Female-to-male jumper wires are used to connect the cathodes and anodes of the LEDs to the breadboard. Regular solid-core wires were soldered onto the terminals of the switches and used for breadboard connections. Two male-to-female wires that are connected to the two ends of the induction coil extend outside of the base through a hole, and are used to connect to the oscilloscope probes.

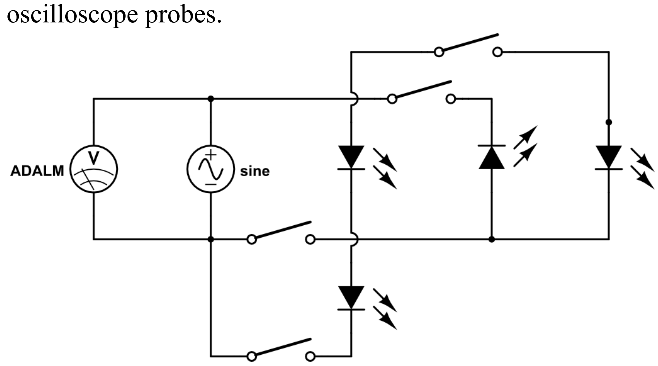

Fig. 5. LED circuit in the Faraday's law experiment. The AC voltage source represents the generator constructed with magnets and an induction coil in the experiment.

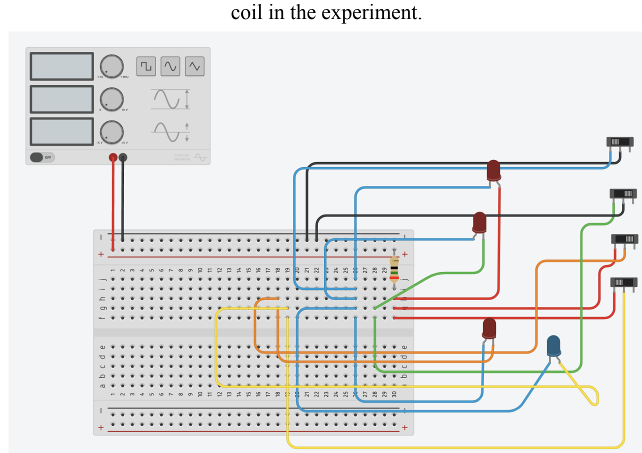

Fig. 6. Wiring diagram of the LED circuit. The resistor in the diagram is only for simulation purposes and is not used in the actual implementation of the experiment, as the induced EMF is low and no current-limiting resistor is needed.

B. Ampere's Law Experiment

As mentioned in the design trade studies, our experiment is modeled after the actual discovery of how an electric field induces a magnetic field. Fig. 7 shows the circuit schematic for when each battery is connected.

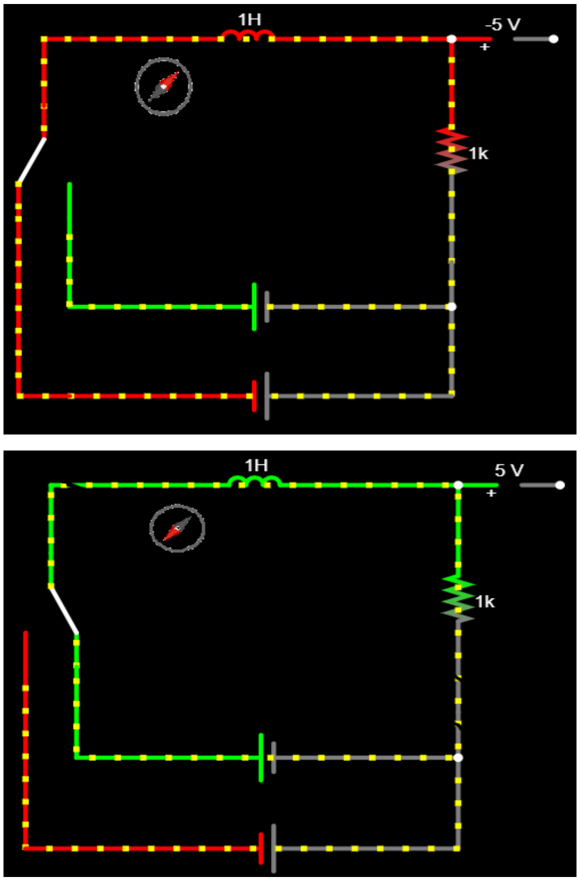

Fig. 7 Schematic of the Ampere's law experiment

The circuit connects two 9V batteries in parallel to a solenoid in series. The solenoid (as represented by the inductor in the schematic) is used to generate the magnetic field that deflects the compass placed beside it.

Our circuit uses a SPDT switch that can alternate between two batteries set up with opposite polarities. The reason for using two oppositely oriented batteries is to show how the change in direction of current results in an opposite magnetic field, which causes the compass to deflect in the opposite direction. The SPDT switches come with an ON/OFF/ON configuration, where the OFF allows us to disconnect both batteries to prevent them from discharging.

As an addition from the design review, we added a galvanometer in series to the solenoid to show the user the direction of the current flowing across the solenoid. This aids in the visual learning aspect as the user can see the galvanometer and the compass deflect together when the switch is pushed in either direction.

The only user-operable part of this experiment would be the SPDT switch, hence it will be the only component placed outside the clear, protective casing. The compass will be mounted within the casing such that the needle's deflection is clearly visible for the user.

C. *Web Application*

For the web application, it was implemented using the Django Model-View Controller framework. The web application is displayed to the user via a laptop, where the user can navigate through the web page using a mouse or trackpad. Clicking on links, entering input boxes and popups will send GET HTTP requests. The Python based Django controller (which corresponds to the files views.py, urls.py, and forms.py) receives these requests and can modify information in the models and correspondingly changes the displayed web page. More specifically, views.py interprets the received GET requests, and can send context variables, including objects in the model to the HTML pages, which can dynamically receive these variables. The way that the variables are displayed on screen can also be changed through the HTML files. Additionally, the front end contains a javascript controller that can send XML requests to the views. These XML requests can similarly be interpreted by the controller as HTTP requests. This allows the HTML pages to update information in real time without having to refresh the page. This was used both to create pages to edit the content in the web application live, as well as display animations through the web app for the Faraday's law experiment.

Models are used to represent database entries, and can be used to store and manipulate information stored in the SQLite database without running any database commands explicitly. This allows for better security of the database as well as easier management of the database. Using the controller, new Models can be created and saved into the database, and old Models can also be read and updated, and can also be sent as context variables to the views. These models are used to store information, such as the educational content of the web application (including quiz exercises as well as images) and scores on the leaderboard for the quiz. For the navigation through the website itself, refer to the wireframe in Fig. 10 in the appendix.

The wireframe shows the routes that a user may traverse through when using the site and shows the HTML pages that have been implemented. Users will start at the welcome page, where they enter a temporary nickname. Administrators can log in through this page, and can then update the web application and content for the two experiments by adding new modules, new pages to each module, or editing existing modules. From the user side, after the welcome page they will be directed to the module home, and are asked about their previous experience with physics and electromagnetics.

There are 3 different possible difficulties of modules that they could be directed to from this point, one for students with no experience, one for students with basic knowledge in physics, and one for students who have already learned E and M. Each module contains different sections and includes images, and quiz exercises to test students' knowledge after each section. Students can also jump between different modules and difficulties at any time through a dropdown menu. After completing the modules, the users will be directed towards an experiment page, where they can interact with the experiments and contains explanations about each experiment and some graphs showing real time values from the experiments. Then, there is a quiz at the end of the experiments where students receive points based on how quickly and correctly they can answer the questions.

D. *Hardware-Software Bridge*

An ADALM2000 is used to sense the voltage data from the two experiments and transmit it to the web application. To utilize the oscilloscope function of the ADALM, we connected a Digilent BNC adapter board to the ADALM, and then connected two oscilloscope probes to the BNC adapter board. The two probes are placed across the induction coil in the Faraday's law experiment and the electromagnet in the Ampere's law experiment, respectively.

A data processing script is used to collect and filter voltage data from the ADALM. The libm2k Python library is used to interface with the ADALM, which allows us to set the sampling rate and period and enable the oscilloscope channels. The noise from the data is then filtered out with a low-pass Butterworth digital filter from the SciPy.signal library. Fig. 8 shows the unfiltered vs filtered signal. A plot is then created and updated with the filtered data using the Matplotlib library, which is then integrated into the web application.

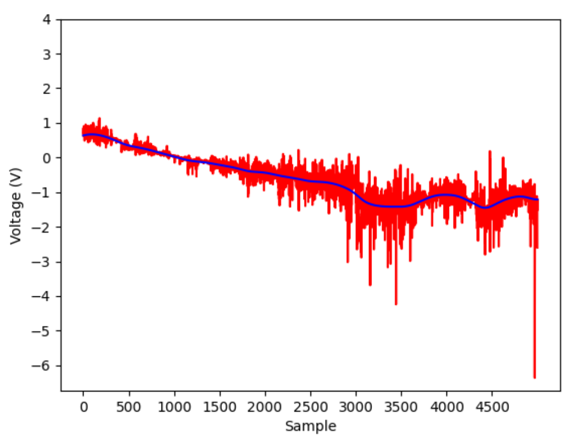

Fig. 8. Filtered (blue) and unfiltered (red) signal measured by the ADALM oscilloscope

VII. Test, Verification and Validation

Our quantitative requirements for the design were to have visual indications of physical phenomena, accurate measurements, low latency and high repeatability of experiments.

A. *Accuracy*

We first tested the accuracy of our voltage readings. We did that by comparing the maximum peak to peak voltage recorded in Scopy to the voltages recorded on the web app via the ADALM. We were within our passing criteria of a maximum 3% error rate. This was expected as the ADALM oscilloscopes are very accurate themselves.

To ensure low latency for the web app animation update when we make a change to the physical circuit, we timed the time between when the crank is first turned to when the web app updates its graph, and we were within our passing criteria of a maximum 1 second latency.

B. *Repeatability and reliability*

To test the repeatability and reusability, we wanted to ensure the circuits last for around a 1000 attempts (any physical change made to the circuit). We tested that with the help of a power drill running continuously for around 1.5 to 2 minutes as shown in the final presentation. That helped ensure our experiment could last for long periods of repeated usage. For the Ampere's law experiment, we essentially used the ADALM signal generator to produce an AC signal for the solenoid that would continuously deflect the compass to ensure it lasted for many rounds of battery polarity changes. Both the experiments passed the tests, ensuring our design is robust.

C. *Effective visual indicators of physical phenomena*

To ensure that the induced EMF in the Faraday's law can turn on LEDs, which act as visual indicators, we rotated magnets in the experiment by hand and used an oscilloscope to measure the induced EMF. Fig. 9 shows that a peak-to-peak voltage of 4.54 V was achieved at 6.65 Hz, which is higher than the turn on voltage of a red LED. Further testing proved that the induced EMF was able to turn on two red LEDs in series, and a red and a blue LED in parallel.

We also measured the current flowing into the electromagnet in the Ampere's law experiment to be around 2 A. The induced magnetic field strength is approximated to be 5.7 mT with Ampere's law. The needle of the compass was deflected significantly (~180°) when the direction of the current flowing into the electromagnet switched.

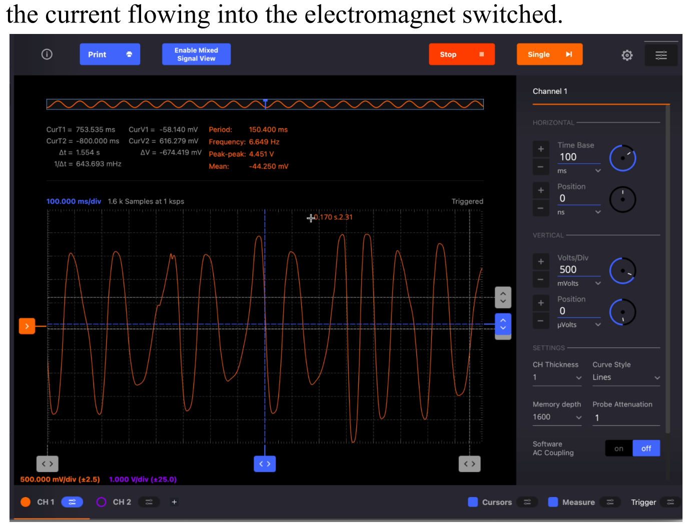

Fig. 9. Induced EMF in the Faraday's law experiment.

D. Accessibility

Through visual inspection, we confirmed that the web application modules use the same Sans Serif font consistently in the text and Arial for the titles to increase the readability of the text, especially for people with dyslexia [6].

VIII. Project Management

The following section describes our project schedule, team member responsibilities, the bill of materials, and risk management.

A. Schedule

Fig. 11 in the appendix reflects our schedule for the project. Each of the parent tasks and milestones are indicated with black bars. Each parent task is split into 2 or 3 sub-tasks that are colored green, blue and pink in order of their start dates. Some sub-tasks are ordered such that they could only begin after the previous one ended, and this relationship is reflected with a blue arrow. The orange tasks are single tasks that are not dependent on other parent tasks for completion.

Our Schedule remained relatively unchanged from the design review, other than a three-week extension to our experiment creation as we took some more time ideating and trying alternatives that were discussed in the design trade studies.

B. Team Member Responsibilities

The team member responsibilities are divided into primary and secondary responsibilities and reflect the milestones (black bars shown in Fig. 11.).

1) Aaron Lao

- Designing web application
- Web to user delivery interface
- Web application content development

2) Shizhen Liu

- Designing and building the Faraday's law experiment
- Designing and laser cutting the cases for the experiments
- Constructing experiment cases
- Web application content development
- Researching and implementing the hardware-software bridge for ADALM
- Implementing the data-processing script

3) Mudit Mishra

- Designing and building the Ampere's law experiment
- Constructing experiment cases
- Web application content development

C. Bill of Materials and Budget

The Bill of Materials and Budget is included at the end of the report, as Table II.

D. Risk Management

A critical risk in our project was communicating the voltage data from our experiments to the web application for the update of the induced voltage values and animations. We initially planned to use the Arduino MKR to read the voltage data for the experiments but were not too familiar with using it. Furthermore, after some trials, we determined that the sampling rate and accuracy of the voltage readings from the Arduino was relatively poor and not meeting our design requirements.

To manage this risk, we researched alternatives like using the ADALM to sample the voltage values. We knew the ADALM was faster and more accurate from our experience using it in the 18-100 class. It was the integration of the ADALM with the web application that took more time, however we had expected that when planning our schedule for building the experiments. So we effectively managed our risks by researching alternatives early and leaving significant slack time in our schedule to account for such issues.

IX. Ethical Issues

Due to the educational nature of our project, the main ethical issue is related to the correctness of the educational content. The content should be accurate and correct at the minimum so that users are not misguided, and should ideally also be intuitive and instructive, so that people can grasp the knowledge easily. Otherwise, people can become confused and lose interest in learning E&M. To mitigate these potential adverse impacts, the educational content can be constantly improved and edited based on feedback solicited from user feedback.

Another ethical issue related to the project is the health of the users. Because the experiments are intended to be used by many and touched frequently, the possibility of spreading germs is quite high if the surfaces are not properly sanitized. Therefore, to protect the physical health of the users, the experiments, especially the high-touch areas such as the switches and the knob, should be sanitized frequently.

Lastly, the safety of the users is another ethical concern. For the experiments to be safe to operate, we ensured that the wires are insulated and enclosed inside cases, as a user may touch an exposed wire by accident and get shocked. Although the voltages and currents involved in this project are low, getting shocked can still be an annoyance and negatively affect the user experience. Therefore, it is important to inspect the experiments periodically to ensure wires remain insulated and inaccessible to the users.

X. Related Work

While there is no large-scale education product that explains the Maxwell Equations, we do acknowledge the presence of smaller-scale experiments that Teachers and Professors make for their own classes to explain Faraday's law or Ampere's law.

Our project differs from these smaller-scale experiments by first being an integrated system for both experiments. We modeled our project after booths that are seen in science museums, with the intention of making our experiments robust and reusable for multiple users over an extended period. This would help us to achieve our goal of educating students of different levels about Maxwell's equations and their importance to our daily lives.

Another key difference is that our project integrates an interactive web application component connected to our physical experiments that is rarely seen in experimental booths. This allows our project to be unmanned, while providing real-time feedback to students and visitors as they access our experiments. We believe this will help improve the learning experience of students, which is the main goal of our project.

XI. Summary

Overall, The Well of Maxwell was able to meet the user and design requirements that we set forth. The experiments clearly demonstrate Faraday's law of induction and Ampere's law. Intuitive visual indicators, such as LEDs, compass, and galvanometer, were used to reflect both the amplitude and direction of the magnetic field in the Ampere's law experiment and the induced EMF in the Faraday's law experiment. The two experiments are also integrated with the web application through an ADALM and the libm2k library. The web app is able to display plots of the induced EMF and the voltage across the solenoid with a delay that is acceptable. However, the delay is certainly a limit on the system's performance. Another limit is that the quality of the educational content can be improved and more thought-provoking quiz questions can be made.

To improve the system performance:

- A better knob can be fitted onto the Faraday's law experiment to make turning the magnets easier
- The oscilloscope plots on the web app can update more seamlessly and more functions can be included, such as the ability to change the time and voltage scales
- The Faraday's law experiment can be gamified in the web app by creating a leaderboard of people who induced the most EMF with the experiment
- The educational content can be edited and improved based on feedback from users
- More quiz questions can be written

The most important lesson we learned through designing and implementing The Well of Maxwell is the engineering process. We also learned the importance of considering the use-case when designing a product. For example, because the experiments are intended to be similar to kiosks at science centers, we decided to enclose the LEDs in the Faraday's law experiment inside a case, so that people cannot tamper with the experiment. Another important lesson is the importance of making incremental changes and improvements on an existing design. For example, the Faraday's law experiment was prototyped first with a cardboard frame. Once the concept was proven feasible, we laser cut an acrylic frame for the induction coil and magnets. Later, we added LEDs, wires, and switches to make the experiment more involved.

Last but not least, the principle of our project is letting people *learn by doing*, and through building the Well of Maxwell, we nonetheless learned by doing ourselves as well. Therefore, we want to emphasize the value of experiential learning. As the ancient proverb goes, "*Tell me and I forget, teach me and I may remember, involve me and I learn.*"

Glossary of Acronyms

ADALM: Analog Devices Active Learning Module
BNC: Bayonet Neill–Concelman
CSRF: Cross-site request forgery
EMF: Electromotive force
E&M: Electromagnetism
FPS: Frames per second
HDF: High density fiber
LED: Light-emitting diode
MVC: Model–View–Controller
SPDT: single pole double throw
Web app: Web application
XSS: cross site scripting

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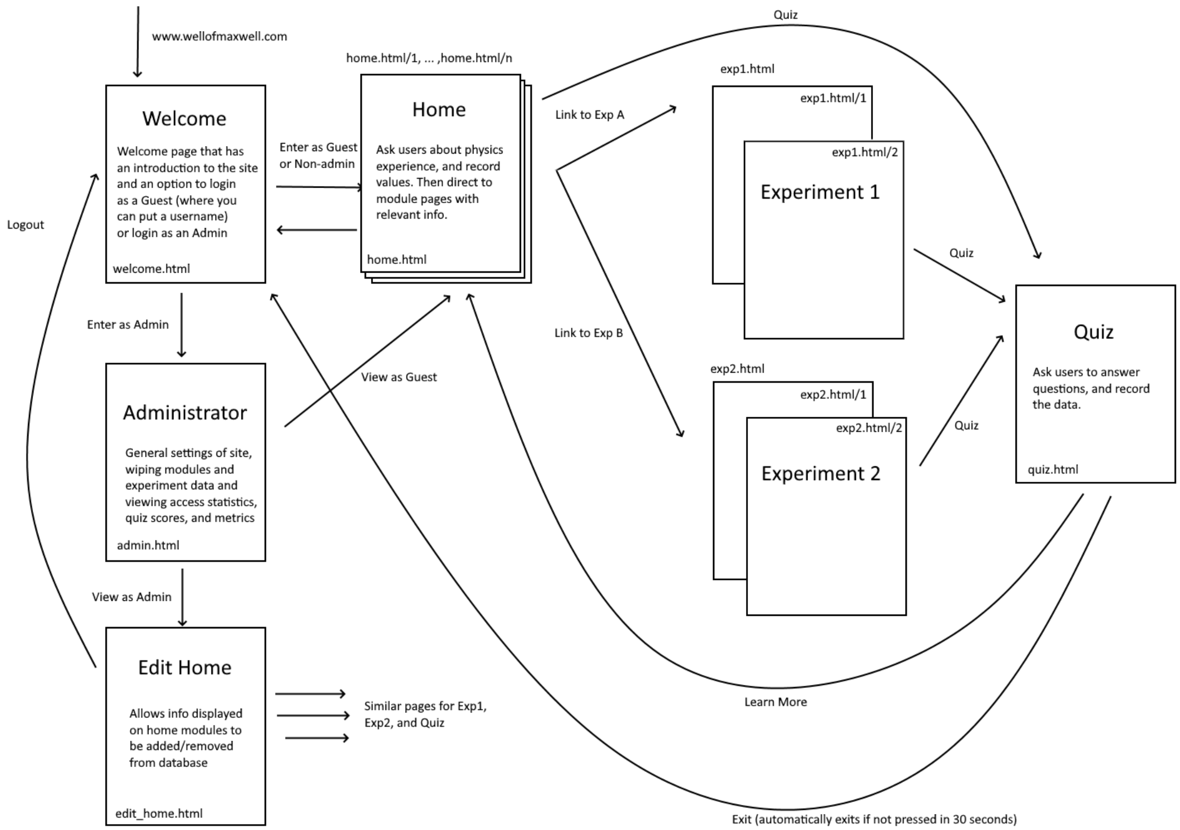

Fig. 10. Wireframe for the web application.

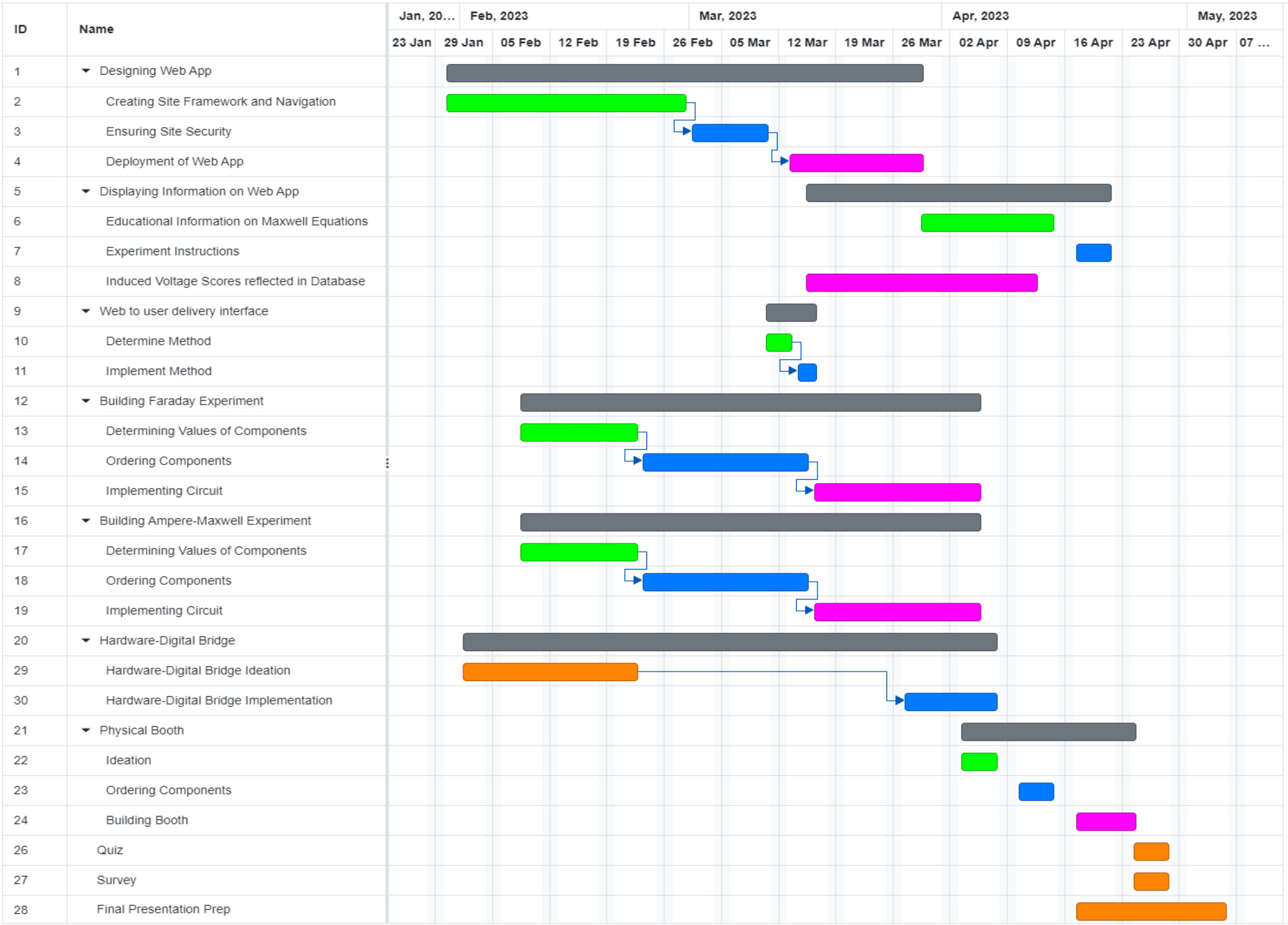

Fig. 11. Gantt Chart for the project, indicating relationships within tasks and milestones (black bars)

Table II. Bill of Materials

Item	Used?	Added after Design Review?	Model #	Manufacturer	Quantity	Cost per Item	Total
Plywood/HDF	Yes	Yes	NA	NA	4	$3.50	$14.00
Acrylic	Yes	Yes	NA	NA	4	$7.00	$28.00
Ferrite Blocks Ceramic Magnets	Yes	No	NA	BY JMY	12	$1.75	$20.99
Neodymium Bar Magnets with Screws	No	No	NI60-4P	DIYMAG	4	$3.25	$12.99
9V Battery Holder	Yes	No	NA	LAMPVPATH	5	$1.80	$8.99
Induction Coil with Primary and Secondary Coils	Yes	No	WD4189	QWORK	2	$13.47	$26.94
SPDT Switches with ON/OFF/ON Configuration	Yes	No	MTS-103	Taiss	10	$0.80	$7.99
Switches ON/OFF Configuration	Yes	Yes	MTS-101	Taiss	10	$0.80	$7.99
Baseplate Compass	Yes	No	NA	TurnOnSport	1	$9.49	$9.49
Enameled Copper Wire	Yes	No	ECW28AWG025LB	bntechgo	2	$11.45	$22.90
Arduino MKR1010 WiFi	No	No	ABX00023	Arduino	1	$38.60	$38.60
ADALM2000	Yes	Yes	505-ADALM2000-ND	Analog Devices Inc.	1	Free	Free
9 Volt Batteries	Yes	No	ZX-55	Energizer	2	Free	Free
Wire Spool Set	Yes	No	CECOMINOD052239	Adafruit	2	Free	Free
Crank	No	Yes	NA	OTURGC	1	$11.89	$11.89
Galvanometer	Yes	Yes	Shanrya3yuqnmd92f5071	Shanrya	1	$18.18	$18.18
Alligator clips	Yes	Yes	WG-026	W&G Global Electronics Inc	10	$0.62	$6.19
Female to Female Jumpers	Yes	Yes	B01L5ULRUA	GenBasic	80	$0.08	$6.49
Total	**$241.63**						