The Well of Maxwell

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***Abstract*—In this design review, 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 Arduino 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*—Ampere-Maxwell's Law, Arduino, Education, Electromagnetism, Experiments, Faraday's Law, Maxwell's Equations, Web Application**

I. Introduction

Electromagnetism (E&M) is an important branch of physics that is fundamental to many aspects of modern society, such as electrical engineering, information technology, and computers. 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. 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 see 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 electromagnetism in a fun, visual and effective way and provide them with intuition and inspiration for further study through an interactive booth housing 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 are high school students and college underclassmen. Although the experiments are the same, we will tailor the analyses of the phenomena on the web application towards people with different levels of prior knowledge of E&M.

II. Use-Case Requirements

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 deliver a satisfactory user experience, the animations on the web application should run smoothly. The device will also feature interactive games built into the web page that users can play as well as hands-on experiments, which need 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.

To ensure that the device is instructive, the content taught through the modules must represent correct electromagnetic theory. Users with differing background knowledge must also be able to benefit from the device, so there must be different modules for students with various educational backgrounds. There will be 3 different possible sets of modules, first for students with no physics experience, second for students with physics experience but no E&M experience, and third for students with previous experience with E&M. The voltage measurements in Faraday's experiment displayed on the web application must be within 5% 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. To ensure a smooth learning experience, the product must have 1 second latency at most between the time the experiment starts, and the time information is displayed on screen. Anything beyond a 1 second latency may cause frustrations when users are learning from the device.

To ensure safety and repeatability, there must be a separation between the user interface and experiments. 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 experiment slider or the Ampere-Maxwell experiment button. The web application also must be secure against SQL injection, XSS attack, and CSRF attack.

III. Architecture and/or Principle of Operation

The basic framework of the system is as follows: the user will navigate through the web application via the touch screen laptop provided on the display table, and will be directed to the appropriate educational modules, which will all be displayed on the touch screen laptop. The web application will display content stored in the SQLite Database by administrators. After completing the educational modules, they will be given instructions on how to perform each experiment through the laptop web application. For the experiments themselves, users will be able to interact with either the Ampere-Maxwell Experiment or the Faraday's Experiment and will also be able to observe visual changes in each experiment as it is being conducted. The data from the experiment after it is completed is sent via pin connection to an Arduino, which will then send the data to the touchscreen laptop through a local USB connection, and the values will be updated in real time as the database updates through HTTP requests between the web application and the laptop. Below, there is also a mockup model for how the booth will look: The touch screen laptop will be placed in the center of the table and the two experiments will be placed on opposite sides of the laptop.

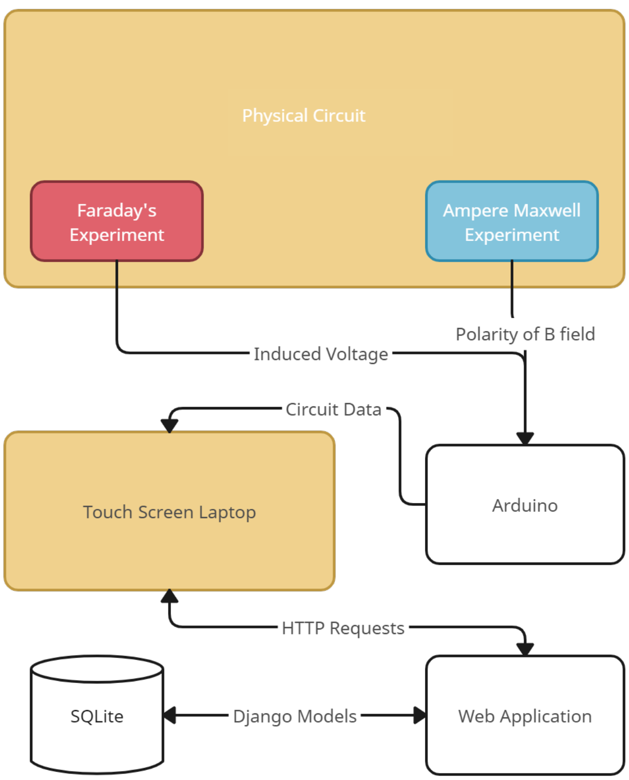

Fig. 1. Block diagram of the booth.

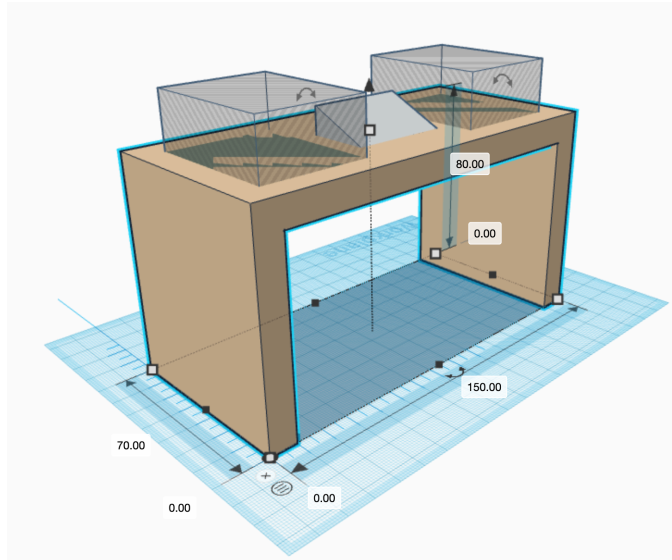

Fig. 2. 3D model of the booth.

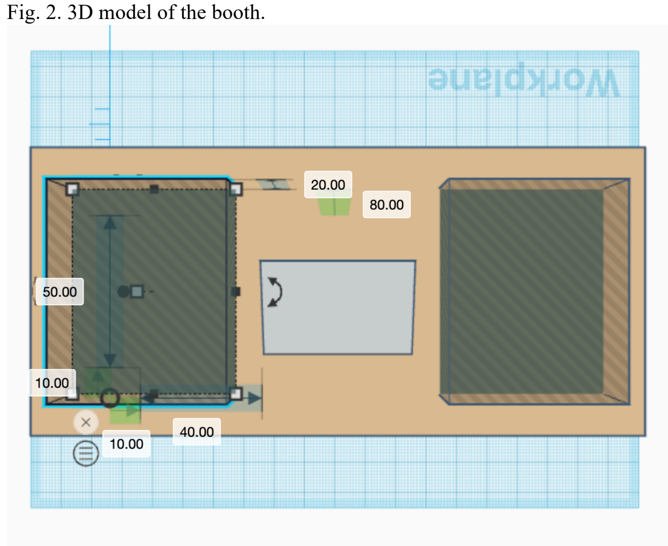

Fig. 3. Top view of the booth, with dimensions of the case.

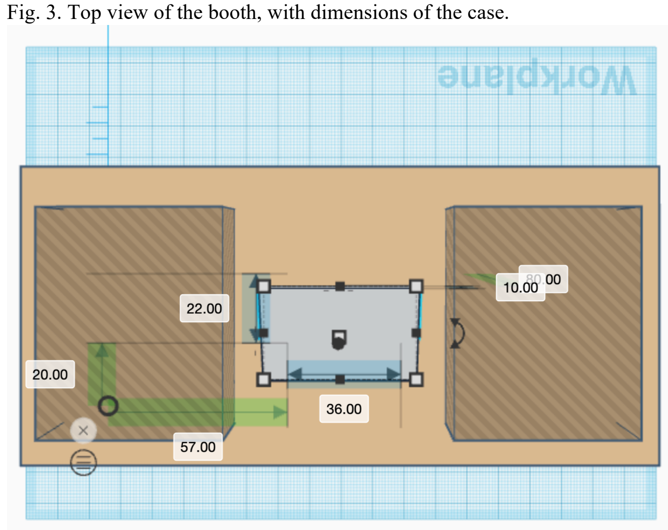

Fig. 4. Top view of the booth, with dimensions of the display.

IV. Design Requirements

You must explain how the most critical constraints relate to the problem you chose to solve as described in the Introduction and the Use-Case Requirements sections. These connections between the design requirements and the use-case requirements may require numerical derivations. If so, please use equations (formatting equations is described later in section **Error! Reference source not found. Error! Reference source not found.**. Number the equations if you need to refer to them later. Otherwise include the equations in-line – but use the equation editor to write any equations you use in your document.

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. Moreover, the content shall be examined and verified by at least three people with expertise in E&M, such as professors and PhD students in the physics or electrical and computer engineering departments of Carnegie Mellon University.

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. To do that, the web application should update every 500ms or less, and the parallel action of scraping the database and updating the values should take less than 100ms each time. Each voltage data sample should be sent from the Arduino to the local server in less than 1ms, so that at least 500 samples can be transmitted in the remaining 500ms, which should be sufficient to infer the actions taken by the user with the experiment.

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, 3/16'' plexiglass cases. To ensure the cybersecurity of the web application, all input boxes should be sanitized to avoid cross site scripting (XSS) attacks. SQL injections should be prevented by verifying user inputs and parametrized queries with prepared statements, never using input directly. Cross-site request forgery (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*

Faraday's law of induction states that a time varying magnetic flux through a surface induces an electromotive force (emf) at the boundary of the surface. Therefore, 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: electromagnets and permanent magnets. 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.

Two experiments that use the second principle 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.

Ultimately, we settled on raising and dropping a magnet placed inside an induction coil with a pulley to demonstrate Faraday's law.

B. *Ampere-Maxwell Experiment*

The Ampere-Maxwell law is defined as follows:

$$\oint \mathrm{Bdl} = \mu_0 I_{enclosed}, \quad (1)$$

where $B \cdot dl$ is the scalar product of the magnetic field and vector segment of the path, $\mu 0$ 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.

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 chose this setup as an 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, Software, and Hardware-Software Bridge

In this section, we will analyze the design choices about the software and web application and compare alternative solutions to our use case requirements. Outside of Django, which is used for this application, the main competitive web frameworks are: Flask, SpringBoot, RubyOnRails, and Angular, ViewJS. Flask and Django are the only two frameworks out of this list that utilize Python, which has several advantages: fast development speed, preferred by project members, and is a simple yet powerful language that is easily scalable. Between Flask and Django, Flask provides greater flexibility, while Django projects offer dynamic HTML pages and provide greater security features and scalability. Since this product requires dynamic HTML pages with crisp animations and real time updates to user feedback, Django’s advantages outweigh that of Flask.

For the choice of database, the most common industry databases used are Postgres, MySQL, SQLite, MongoDB, DynamoDB. SQLite has good integration, free access, and of the options from this list, it is the most lightweight and simple to use. Since this product is focused on the front-end display and user experience, the database does not require high complexity and will not store an extensive amount of data and does not require high throughput parallel access. Thus, this project will utilize SQLite rather than a more complex database system.

For front end options, the most common choices are Native HTML + CSS/ JS, ViewJS, React, Angular, and Bootstrap. Bootstrap is simple to use yet powerful, provides clean and consistent design with other frequently used web pages, provides dynamic animations, and is preferred by experience from the project members.

Additionally, there were considerations on how the web application should be run. If the web application was to be deployed on the cloud, the common choices for deployment are AWS or Heroku. However, after further consideration, the web application does not need to be deployed, as it can simply be accessed through the touch screen. Users will not need to access the site through their own devices, as there will be a touch screen provided and the touch screen will be closely linked to the experimental data. Thus, running the web application locally is sufficient, and there is no need for the module to be fully deployed.

For the hardware interface, there are many options to read information from the circuit and relay it to a computer. For this device, Raspberry Pi and Arduino were considered. Since the device only needs to relay voltage data and voltage polarity data, the cheaper but less robust Arduino is perfectly capable of reading this data from the circuit through a pin connection and has multiple options for sending it to the web application, including sending the data through an AWS server, or using a local python script to read data from the Arduino. Since it was decided that the web application does not need to be deployed, reading the data through a local python script and USB connection to the Arduino is faster and simpler to set up. Thus, this device will use a local connection between the laptop and the Arduino through a USB cable.

VI. System Implementation

The following section details the specific implementation of the respective subsystems within our project.

A. Faraday’s Law Experiment

Fig. 5. shows the overall design of the experiment for Faraday's law. The two arms of a stand hold a pulley and a piece of PVC pipe. Two neodymium disk magnets, each one with a thickness of 0.5 cm, a radius of 1.25 cm, and a countersunk hole for #10 screw, will be secured to the string of the pulley, and a weight is attached to the end of the string. Both the magnet and the weight can pass through the PVC pipe. An induction coil is wound around the PVC pipe. A red and a green LED (which typically have the lowest turn on voltages) will be soldered to the two ends of the induction coil with opposite polarities (not shown in the figure). When the magnet passes through the induction coil, the magnetic flux through the coil will change and an emf will be induced, which, if sufficient, will turn on one of the LEDs.

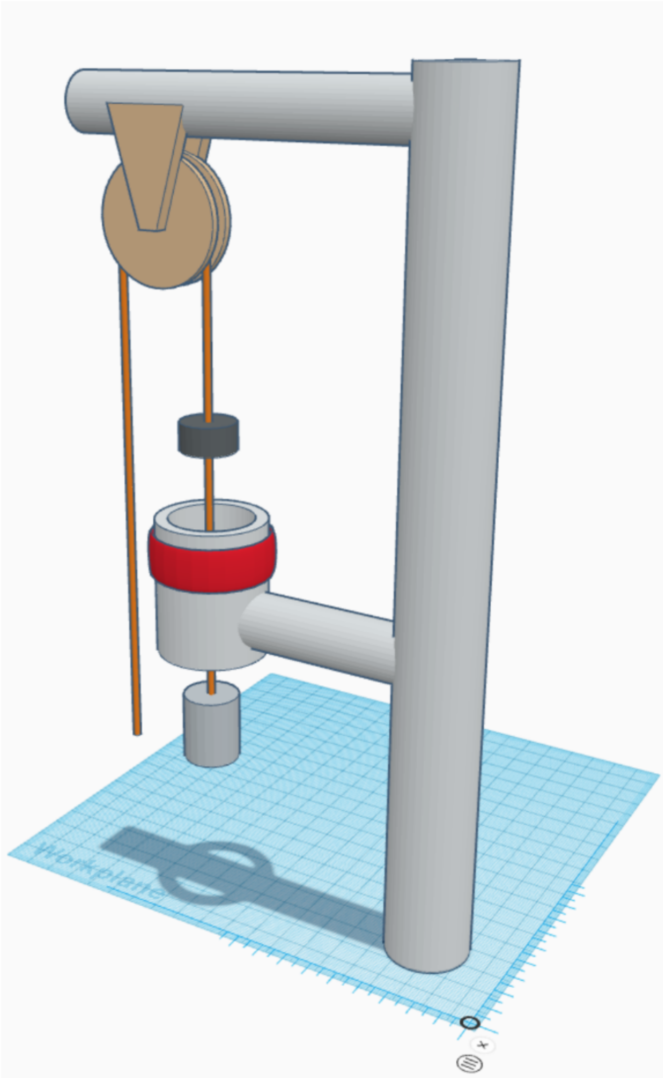

Fig. 5. 3D model of the Faraday's law experiment, showing the magnet, pulley, induction coil, and weight.

We now derive the specifications for the key components measured above.

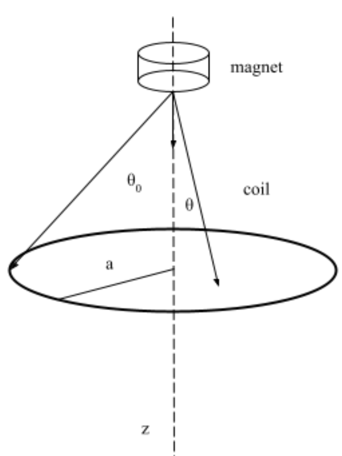

Fig. 6. Magnetic flux calculation for the magnet and coil.

Because the magnet is relatively small, its magnetic field may be approximated with a dipole model [1]. Thus, the magnetic field of a dipole moment, m, can be expressed as

$$B = (\mu_0/4\pi)\ (m/r^3)(2cos\theta\hat{r} + sin\theta\hat{}\theta), \qquad (2)$$

where r is the radius of the induction coil. Then the surface element of the magnetic flux through the circular coil can be calculated as

$$B\ dA = (\mu_0 m/4\pi r^3)2cos\theta r^2 sin\theta d\theta d\phi. \qquad (3)$$

Integrating the magnetic flux surface element yields

$$\Phi = (\mu_0 mN/2r)sin^2\theta_0, \qquad (4)$$

where N is the number of turns of the induction coil. The flux, in terms of z, is then

$$\Phi = (\mu_0 mN/2)\left(a^2/(a^2 + z^2)^{3/2}\right) \qquad (5)$$

Using Faraday's law of induction, we derive the induced emf as follows:

$$V = -d\Phi/dt = (3\mu_0 mNa^2/2)\left(zv/(a^2 + z^2)^{5/2}\right), \qquad (6)$$

where v is the velocity of the magnet. To find the maximum induced emf, we take the derivative of V and find the values of z such that V'= 0. Therefore, the maximum induced emf is

$$V_m ax = \pm 24\mu_0 mNv/\left(5^{5/2}a^2\right), \qquad (7)$$

which occurs at $z = \pm a$.

The induced emf should be more than the turn of voltages of the green and red LEDs, which are about 2.0V and 1.7V, respectively. A magnet's dipole moment is not easily calculated and is often measured empirically. According to the vendor of the magnet, K&J Magnetics, the combined magnetic dipole moment of the magnets used should be 5.68 Am^2. Therefore, if N = 400, v = 2m/s, m = 2.88 Am^2, and a = 3cm, then Vmax should be about 2.72V.

For the velocity to be 2m/s, the distance between the pulley and the induction coil should be about10 cm, according to the kinematic equation v=2$a\cdot r$, where r is the distance traveled by a particle.

B. Ampere-Maxwell 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. The images below show the circuit schematic for when each battery is connected.

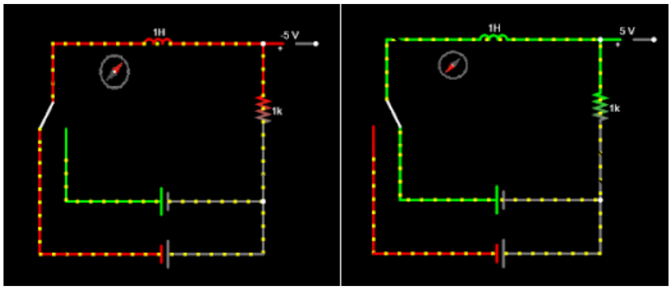

Fig. 7. Circuit schematic of Ampere-Maxwell Experiment with both battery polarities depicted respectively.

The circuit connects a 5V power source to a 1 kOhm resistor in series that drops about 4.98V in practice. 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 single pull double throw (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 for discharging.

The experiment will use 9V batteries that will be regulated to 5 volts by a power supply. This is done to ensure that we produce a stable voltage even as the battery discharges over repeated experiments. As an alternative, we are also considering using Scopy as our power supply to guarantee a fixed 5 Volts over repeated uses.

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. *Software System*

The software system will be implemented using a Django framework, using Model-View-Controller model to control the Web Application. The web browser will be displayed on the touchscreen laptop, where user actions correspond to GET or POST HTTP requests. These requests are received by the Django framework in the controller, which is made up of urls.py, views.py, and forms.py. The file views.py has functions to interpret the various kinds of requests and send the appropriate context variables to the views, which returns an HTTP response and routes to a static HTML file that will be displayed as the current web page and will be reflected in the touch screen. These HTML files can also be dynamically updated with JavaScript (utilizing AJAX), which can run scripts on load or on click and dynamically build HTML elements in real time. The JavaScript file also can send XML requests, which are received by the controller (views.py file) and return HTTP responses back to the views. Additionally, the JavaScript file can make requests to call a controller function to check the database to see if new data has been sent in by each experiment and update the information through the Controller – Model connection. Then, the information will be updated within the View as the controller passes the updated information to the view.

The models can also be accessed through the controller (views.py file) and correspond to updating changes reflected in the database. Similarly, uploaded images can be probed from the database by using the controller and sent via HTTP responses.

The layout of the website itself is shown through the following wireframe, which shows the possible paths that users will traverse as they navigate the site and the HTML pages that we will have to design and implement Users will start at a welcome page, where they will enter a name for the leaderboard. Administrators may also log in through verified accounts from this portal, where they can add more educational modules, edit any existing modules, or delete modules. They will also be able to edit, delete, and add more instructional pages to each experiment. A user will see the home page from the welcome page and be asked about their level of experience and background knowledge. Then, they will be directed to the appropriate modules. After flipping through the modules, they will reach the experiment page, which provides instructions on how to perform each experiment and real time feedback values from the experiment. After the experiment is complete, the users can navigate to a quiz, which will assess them on the material covered by the modules and a feedback survey.

D. *Hardware-Software Bridge*

An Arduino board will serve as the connection between the hardware and software.

The analog pins of an Arduino Uno board will be used to measure the relevant quantities in the experiments (induced voltage in Faraday's law experiment, voltage across resistor in Ampere's law experiment). A Python script using the PySerial library will retrieve the data sent by the Arduino through USB connection.

VII. Test, Verification and Validation

As mentioned previously, we have 4 high-level use case requirements (fun, instructive, smooth, safe) with multiple sub-requirements. There is one design requirement for each subsection of the use case requirements. The following sections will detail the tests for each design requirement under the 4 high-level use case requirements.

A. *Tests for Use-Case Specification: Fun*

1) *Game & Experiment*

Our design requirement was to add a gamified component to the Faraday's Experiment. To test that the game and the experiments are fun for the user, we will include a survey at the end of the booth experience where users will rate their overall experience with the experiments. We will quantify these ratings on a scale of 0 to 5, and our aim is to have an average rating of 4.5. This value was chosen as it is similar to ratings received by leading educational applications like Khan Academy on application stores.

2) *User Engagement*

Our design requirement was to have visitors spend about 3 to 5 minutes at the booth to know that they were engaged with the content. To test that, we will ask people from CMU from different majors to use the system and monitor how much time they spent on the machine, aiming for an average of 4 minutes. If the users leave within less than 3 minutes, it implies that our booth was not engaging enough.

3) *Animations*

Our design requirement was to add animations to our web application with at least 30 FPS. To test that, we shall use FPS tracking or recording software (like Windows Game Bar) to ensure our animations remain above 30 FPS.

B. *Tests for Use-Case Specification: Instructive*

1) *Correct Content*

Our design requirement was to refer to authoritative textbooks in Electromagnetics to ensure our educational content is correct. To test this, we will have our modules vetted by a professor in Electromagnetics like Prof. Maysam Chamanzar who teaches the Fundamentals of Electromagnetics course at CMU.

2) *Matching User Knowledge*

Our design requirement was to develop content suitable for users with different levels of background knowledge. To test that, we will source students of 3 categories (no engineering/math background, intermediate math background and new to engineering, advanced math and engineering background) and get their feedback on the ease of understanding of content.

3) *Accuracy of measurements*

Our design requirement was to ensure the Arduino output was within 5% of the true values. Our reference for true values will be a lab grade oscilloscope and its measurements of the induced voltage will be compared to the values read by the Arduino. To pass the test, the Arduino values have to be within 5% of these true values and the DC bias should be less than 10mV.

C. *Tests for Use-Case Specification: Smooth*

1) *Latency*

Our use case requirement was to have a latency of less than 1 second between user input and the animation update on the web application. To test this, we will first measure overall latency by timing with a stopwatch the duration between when the user has an experiment input and when the animation updates. If that comes close to or more than 1 second, we can break down the test to each component by using Scopy to measure latency between the Arduino and laptop connection and using a JavaScript timer to measure timing between database update and display. The combined time of the two components is total latency.

D. *Tests for Use-Case Specification: Safe*

1) Isolation

Our design requirement is to case experiments and only leave user-operable components out of the protective casing. To test this, we can simply ask test users to attempt accessing the physical circuit outside of the user-operable components (switch and magnet).

2) Robustness

Our design requirement to ensure the experiment does not break over 1000 tests cannot be tested manually (as each test would count in the 1000 attempts, not guaranteeing future attempts). Instead, to test this we will use a modular approach by checking that all our components are tested for over 1000 attempts by the manufacturer. If each of the components has been thoroughly tested by the manufacturer, that guarantees the robustness of our system.

3) *Web Security*

Our design requirement was to deploy the web app locally to keep it safe. The CSRF token generation for the web application to be crypto secure is validated by the Django framework. Sanitization will also use the validated Django sanitization function. SQL injection will be avoided by ensuring input validation and parametrized search queries.

VIII. Project Management

The following section describes our project schedule, team member responsibilities, bill of materials with budget and risk mitigation plans.

A. *Schedule*

Fig. 8. shown below 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 can only begin after the previous one ends, 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.

Fig. 8. Gantt Chart for the project, indicating relationships within tasks and milestones (black bars)

B. *Team Member Responsibilities*

The team member responsibilities are divided into primary and secondary responsibilities and reflect the milestones (black bars shown in Fig. 8.).

1) *Aaron Lao*

- Designing web application
- Web to user delivery interface
- Web application content development
- Constructing the physical booth

2) *Shizhen Liu*

- Building Faraday's law experiment
- Constructing the physical booth
- Web application content development

3) *Mudit Mishra*

- Building Ampere-Maxwell's law experiment
- Constructing the physical booth
- 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 Mitigation Plans*

A critical risk in our project is communicating the voltage data from our Arduino Voltmeter to the Web Application for the update of the induced voltage values and animations. No one in our team has had experience with delivering data acquired from an Arduino chip to automatically update content within a web app, which would most likely involve the web application repeatedly accessing data from a SQLite server.

To mitigate this risk in advance, we are researching how to deliver data from the Arduino to the SQLite server and how that data can be repeatedly accessed by the web application. We are also researching alternatives like using APIs that could be implemented in the web app to scrape data from a wifi-connected Arduino chip.

IX. 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 the Ampere-Maxwell 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 the Maxwell 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.

X. Summary

In essence, our product is an educational booth modeled after booths at a science center. The purpose of this booth is to educate people of different age/education levels about the importance of Electromagnetics, specifically the Maxwell Equations. We achieve this by developing educational modules on a web application, as well as integrating it with two physical experiments (Faraday's law experiment and Ampere-Maxwell's law experiment). User inputs in these experiments interact with the web application to update animations and provide measurements that contribute to the gamified components of the experiments. Our web application includes a survey to get information on user experience and a quiz to test if our booth is achieving its learning outcomes.

A challenge in our implementation would be to make our experiments robust and to ensure it lasts over a thousand uses. Our experiment has components that require physical input from a user, such as moving the magnet in the Faraday's law experiment and flipping the switch in the Ampere-Maxwell's law experiment. It would be a challenge to ensure that users do not have the ability to break these components from misuse or an intentional attempt to break the circuits. This would require good physical engineering when designing the booth and the protective casing of the experiment, while ensuring the experiments are easily accessible.

REFERENCES

[1] Robert Kingman, S. Clark Rowland, and Sabin Popescu, "An experimental observation of Faraday's law of induction." American Journal of Physics 70, 595-598 (2002). Accessed on Mar 3, 2023, [Online]. Available: https://doi.org/10.1119/1.1405504

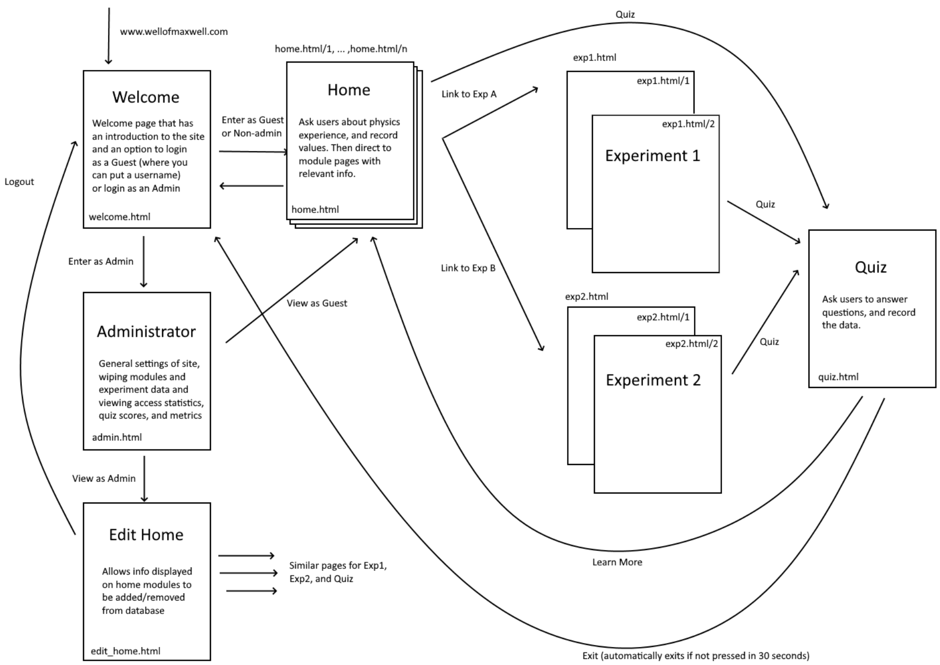

Fig. 9. Block diagram of the web application.

Table I. Bill of Materials

Description	Model #	Manufacturer	Quantity	Cost @	Total
Ferrite Blocks Ceramic Magnets	NA	BY JMY	12	$1.75	$20.99
Neodymium Bar Magnets with Screws	NI60-4P	DIYMAG	4	$3.25	$12.99
9V Battery Holder	NA	LAMPVPATH	5	$1.80	$8.99
Induction Coil with Primary and Secondary Coils	WD4189	QWORK	2	$13.47	$26.94
SPDT Switches with ON/OFF/ON Configuration	MTS-103	Taiss	10	$0.80	$7.99
Baseplate Compass	NA	TurnOnSport	1	$9.49	$9.49
Enameled Copper Wire	ECW28AWG 025LB	bntechgo	2	$11.45	$22.90
Arduino MKR WiFi 1010	ABX00023	Arduino	1	$38.60	$38.60
9 Volt Batteries	ZX-55	Energizer	2	Free	Free
Wire Spool Set	CECOMINO D052239	Adafruit	2	Free	Free
Display Case	NA	SimbaLux	1	$10.95	$10.95
				Grand Total	**$159.84**