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Geothermal Energy: A Super Power Source

SUBMITTED BY:

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Professor K. Schulte Grahame
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Dear Professor Schulte Grahame,

This is Jojowino Engineering's final report for our project "Geothermal Energy: A Super Power Source". It will outline the process we took to complete the project and our individual contributions, including many appendices containing code, pictures, and all other relevant pieces of information.

Throughout the process of designing this exhibit, we realized that the real challenge of this project was not the technical aspect, but the conceptual and social aspects of the assignment. When looking at geothermal energy as a concept, we realized that it would be important to find a balance between demonstrating the process, explaining the ethics, and making the game fun for kids. We wanted to make sure that we all developed our teamwork skills since the project required a high degree of collaboration. Although our personalities did not mesh perfectly from the start, we worked hard on making our group dynamic more conducive to productivity while trying to minimize stress levels. Because of this, we became closer as a team, a group defined by our love of light-hearted humor.

Even though there was a lot of work and stress throughout, we really enjoyed working on this project. It gave us firsthand experience of what the engineering design process entails—from the conception of ideas to prototyping to full realization of the design. We also all learned about the various programs and techniques covered in the class, such as SolidWorks, Arduino, and woodworking. The project required us to learn new concepts quickly, but we managed to accomplish this and present a final product that we are all proud of. Seeing our final project displayed at the Museum of Science was extremely gratifying for us, especially since almost everyone who used the exhibit genuinely enjoyed it.

Thank you for your time and we look forward to your review of our project.

Sincerely,

John Chiaramonte   Joe Durkin   Will Hodge   Noah Foley

TABLE OF CONTENTS

LIST OF FIGURES

EXECUTIVE SUMMARY

Our team, Jojowino Engineering, consisted of Noah Foley, William Hodge, Joseph Durkin, and John Chiaramonte: four first-year engineering students at Northeastern University. We believe in modern sustainability: the practice of meeting a society's needs without infringing on the ability of future generations to do the same. Our problem statement, summarized, declares that, in the current energy crisis Americans find themselves in, better sustainability education is required to help create a future that can rise to face these challenges responsibly. A museum exhibit experience must be created that is fun, interactive, and educationally accessible. After brainstorming topics to use as an exhibit theme, it was decided that the best option to meet the standards of the triple bottom line was geothermal energy. It is profitable, creating jobs and an affordable energy source for many socioeconomic classes. Sustainable or "green energy" is popular right now and seen as a moral, societal responsibility. Finally, it is good for the planet, uses little resources and land, and does not create much byproduct waste. The subject of geothermal energy was also appealing due to its general obscurity among youth. To decide how our project would look/operate, each team member designed a concept drawing of the exhibit. A Kepner-Tregoe Decision Analysis was used to determine which concept would be used. After this phase, we harvested parts and ideas from the lesser drawings to create one cohesive plan.

Geothermal Energy: A Super Power Source is an Incredibles-themed museum experience that teaches users about both the inner workings and the sustainable benefits of geothermal energy. The exhibit is broken down into three main parts—a power plant model, a competitive quiz game, and an informational poster—which all come together to form one streamlined user experience. In the game, users "buzz in" to answer questions about geothermal energy. With each question, a different part of the physical power plant model is turned on and highlighted by an indicator light so that the users can make the critical connections necessary to learn about the geothermal process. The game has 5 total questions designed to teach about different parts of geothermal energy, and it does not end until every question has been answered correctly for maximum educational takeaway.

NOAH FOLEY

1.1 INTRODUCTION

PROBLEM STATEMENT

Fossil fuels make up 80% of energy generation in the United States, [1] and Americans are not mobilizing fast enough to stop greenhouse gas emissions and transition to renewable energy. People do not know what geothermal energy is or how it works, and why it would benefit them and the planet in the long term, so we will design a museum exhibit that teaches children about geothermal energy in an eye-catching and engaging way, while also making it accessible to kids of many learning styles.

INTENDED BENEFICIARIES

The primary user group are elementary school-aged children with little to no understanding of the topics associated with geothermal energy or sustainability in general. They are easily distracted or bored, making it more difficult to maintain their attention than with adults. They are generally too young to have been educated in environmental ethics and the world energy needs. The United States Common Core does not regulate scientific topics, only scientific literacy [2].

The clients are the people who employ the engineers to work. This is Professor Schulte-Grahame, the teacher who assigned the project with a grade as payment. This is marked in proportion to the quality of the exhibit.

SUSTAINABILITY IN ENGINEERING

According to the EPA, sustainability is "Sustainability is based on a simple principle: Everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment. To pursue sustainability is to create and maintain the conditions under which humans and nature can exist in productive harmony to support present and future generations [3]." Engineering can be qualifiable as sustainable in the case that the design in question satisfies the 3 P's of sustainability.

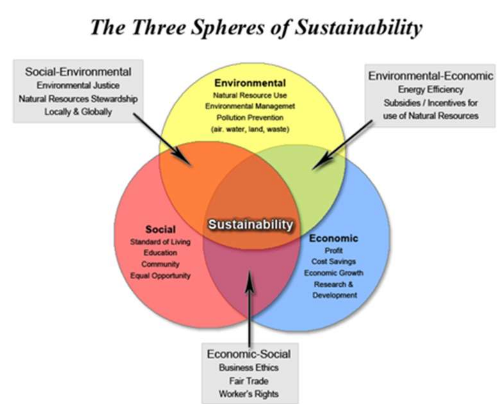

Fig. 1. The Triple Bottom Line [4] as represented by a Venn Diagram, characterizes the three main factors of sustainability.

From Fig. 1, one can see the Triple Bottom Line of sustainability, which notes that a sustainable design or process must benefit or at least not negatively disrupt the people, the planet, and profit.

Geothermal energy is a sustainable solution to use as an alternative energy source because, after implementation, it does not cost much to maintain. It is a source of affordable energy that may provide jobs. It does not produce any harmful emissions, completely recycles all materials used in the energy generation process, and it does not take up a ton of space, leaving room for areas to be developed around a power plant, even in a densely populated metropolitan area like Boston.

To appeal to the public, the social/cultural acceptability of the design must be considered. Does the design improve the standard of living and equality of opportunity of communities and society? Fundamentally, would the public find this design to be good or bad? First, an NYU Stern study suggests, “that both wind energy and geothermal energy are poised to become more economical than fossil fuels within a relatively short time frame [5].” Not only would geothermal energy, a much cheaper form of electricity than oil, increase the standard of living by providing cheap electricity, heating, or cooling, it would also advance equality of opportunity by making electricity more affordable, allowing more people to harness it. Plus, renewable energies are encouraged by society right now; people want to be “green” and try to help relieve the planet of our squandering of its resources.

To appeal to the planet aspect, environmental factors of the design such as natural resource usage and pollution/land management must be considered. In terms of environmental consciousness, geothermal energy uses little land relative to coal mines, due to the plants’ nature of being underground. “An entire geothermal field uses 1-8 acres per megawatt (MW) versus 5-10 acres per MW for nuclear operations and 19 acres per MW for coal power plants,” and “Because of their minimal land use and impact, geothermal power plants also blend in harmoniously with a variety of other land uses. For example, once the geothermal power plant and associated wells are completed, the land can be used for livestock grazing or other agricultural purposes [6].” The only natural resources used by this process are water and the heat of the Earth, which are abundant and renewable.

Fig. 2. Steam [7] being released from a geothermal plant.

From Fig. 2, one can see the only major byproduct of geothermal electric production, steam. Furthermore, most of the water is condensed and reused, so this is relatively insignificant. In the case of geothermal heating and cooling systems, heat is transferred from/to groundwater to/from usable water by conduction. Then, the groundwater heats/cools itself again via a convection cycle, so a steam byproduct is never even engendered.

Finally, to appeal to profit, cost savings, economic growth, and Research/Development are design elements to consider. Geothermal energy carries so much untapped potential for an entirely new energy business that could be a legitimate competitor for many other energy industries such as coal mining, natural gas, and other renewable energies. A 2006 MIT team of scientists estimated, "enhanced geothermal systems could help the United States meet its energy needs 2,000 times over [8]." The affordability of this energy would bring in a demanding market that would allow for cost savings and price optimization while still being one of the least expensive options. The market for this energy or heating/cooling source would create jobs for those who would construct and maintain the geothermal plants. Research would occur to help develop more efficient and productive plants, which would also inherently create jobs in the STEM fields. Currently, much of the country has avoided embracing geothermal energy due to the costliness of initially constructing plants [9]. Demonstrating geothermal systems' boundless value through a project such as the Jojowino Engineering museum exhibit may be the ignition required to get further Research and Development off the ground to begin a cycle of geothermal plant constructions and improvements.

Project Objectives

There were several objectives the exhibit had to meet. First and foremost, the exhibit had to be entertaining and interesting enough to maintain the attention of the young user base. This was achieved by adding a theme that children could relate to such as kids' TV and movies, specifically the Incredibles and an interactive GUI system to truly bring them into the project with what would eventually be an Incredibles-themed trivia game. Another objective was that the exhibit had to be as simplistic and realistic as possible to make the exhibit minimally confusing, even using a humidifier to display a realistic-looking steam.

Fig. 3. The humidifier

From Fig. 3, one can see the humidifier, which is a device that vibrates at a frequency that water vaporizes. The exhibit will also display a working, moving model of a geothermal power plant.

The functions of the exhibit were that it had to effectively teach concepts of sustainability and geothermal energy/heating/cooling to the audience, it needed to be educationally accessible to users of a variety of learning styles, including auditory, tactile, and visual learners, and it needed to positively promote the further research and development of geothermal energy as an ethical energy alternative.

The constraints that had to be adhered were that it had to have chamfered, dull edges and corners to maximize safety, along with not including any parts that could injure someone. The entire project had to be light enough and spatially small enough to be carried long distances with ease. It also had to satisfy the guidelines of Universal Design.

1.2 BACKGROUND

Research

I researched the viability of our project's subject matter of geothermal energy as an ethical option in terms of Value Sensitive Design and its merits as an economically viable option. This included research included how it compared to other forms of energy generation, and what societal problems it could assist to remediate, such as cheap energy for those in poverty with semi-dependable housing. I also researched geothermal processes in general. My groupmates did as well, also categorizing the systems' different formats and abilities in order to inform our Milestone 2 prototype. This research ended up determining which information we wanted to include and prioritize in our poster and game so that we could accomplish our goal of positively promoting sustainability.

Ethics

The problem addressed by the project was the underrepresentation of the subject of human's quest for sustainable energy generation in most American children's education. Their ignorance to this need and the currently developing solutions to energy requirements forebodes a future where people will continue to not do enough remedy this vital contemporary issue. The problem can be considered as significant as the energy crisis people currently face as a society. The homo sapiens species cannot maintain the amount of electrical power required at the rate that nonrenewable resources are used. Renewable and sustainable energy sources must be depended on and capitalized upon so that humans can supply themselves before resources dwindle to nothing. By informing young people about the benefits of geothermal energy as a renewable and sustainable energy option, the subject matter can be promoted from a young age so that the geothermal concept can be ingrained by the time they reach adulthood. At this point, mainstream knowledge of geothermal energy, along with public support for the improvement of sustainable energy generation methods can allow the former to become more present and impactful in the future. In this sense, knowledge literally does become power. This project could also help improve the plague of American poverty, for if facilitated and distributed responsibly, a more affordable source of electricity could be available to the nation's economic lower-middle class and housed lower class. However, everyone would benefit from this source, even the geothermal industry, which could potentially challenge many energy competitors. This project would be considered a success if visible increased comprehension of our key subjects (rudimentary understandings of sustainability and the forms of geothermal energy production) and a positive and optimistic portrayal of geothermal energy could be shown. These are conducive to the idea that positive environmental change can be wrought. The technology that is our project would have to inform about multiple aspects and uses of a specific type of sustainable energy, while simultaneously displaying a need for the method's future development and promotion. Due to the public's general unawareness of geothermal energy and its flexibility of how it is used, this was the best option for educating young people. The technology also had to function as a game, as uninteresting museum exhibits tend to be avoided or left incomplete by elementary-level children. Furthermore, the design itself should include real visual models to help display what the actual process looks like as best as possible. It needs to be tangibly close to a functional geothermal power plant for maximum comprehension. Multiple styles of learning had to be accommodated by the project design in order to reach all users in the optimal mode of learning, so audio recordings may support any visual text included in the game. The exhibit itself is of course a tactile teaching vessel.

A clear alternative to the museum exhibit/game project described here is the indoctrination of geothermal energy into the common core of environmental science learning at an elementary level. If schools were already efficiently teaching the information we are trying to supersede, our project would be rendered redundant and unnecessary, reaching only a microcosm of the masses of America's elementary youth. However, this method is only as strong as both the curriculum mandates instituted by government entities and the teachers who directly teach the subject matter to students.

Fig. 4. The logo [10] of the Massachusetts Department of Education

From Fig 4, one can see that the state of Massachusetts has its own bureau for education, separate from all other 49 states and the nation at large. If a state government's education entity does not prioritize environmental protection, then geothermal energy will not likely be taught well. Unfortunately, the only way to reestablish the focus is to petition these government agencies to reinstate this part of the curriculum. For a movement like this to even be possible, the issue of geothermal energy must be kept in the public eye once it is initially captured. Otherwise it will be like starting afresh, with no one, government nor public, knowing or caring about the innovation. Furthermore, a byproduct of this universal education of the subject matter could result in a stagnancy in progress. Children taught this could very well grow up and have no ambition to revolutionize the way humans gather energy. Schools too often teach without calling students to act upon what they learn. The exhibit's game has not propagated this troubling lack of invocation due to its direct message to young users that geothermal processes are good and should be supported. To avoid this issue in the alternative solution, the future of the renewable resource needs to be implied in some way. In other words, the next steps people must take to advance geothermal energy's influence in the public energy system should be recommended. Kids should know what they can now or eventually contribute.

Universal Design

Universal design is a set of guidelines and principles that outline the design of physical demonstration mediums like exhibits, used by institutions such as the Boston Museum of Science. Universal Design [11] is intended to make displays and exhibits as universally accessible as possible, with recommendations to optimize visibility and the ability to interact with its features, while having guidelines to allow the handicapped to easily place themselves in front of it. Plus, a major feature of the societal third of the sustainability triple bottom line is equal opportunity, so that should be present in how the project is presented as well. In designing the features of this exhibit, it was ensured that the touchscreen surface was raised 45 degrees above the horizontal, the body text fonts were all sans serif 30 pt. without boldface or italics, and the touchscreen was placed near the front of the exhibit so that it met the arm reach distance maximum of 20" from table's edge. The table that was used on the day of the exposition was ensured to be at least proper height, width, and pull-in length for wheelchair accessibility, respectively 27", 30", and 17", all contributing to Universal Design.

1.3 METHODOLOGY & ORGANIZATION

Per our team contract, we began every Milestone by sharing our schedules or upcoming events to allow the group to plan around them. We then held a meeting, creating a list of what we were going to accomplish chronologically and who would pursue each task. I tracked this schedule in a Gantt chart, a time management system that keeps track of when every task should be completed in order to not fall behind, lose work quality, or rush. We tried to biblically fulfill the Gantt chart's requirements. An unspoken rule indicated that all members should be present on all "build days," so we coordinated what times we could meet the day before each of these for the sake of organization. Communications and updates were conducted daily via WhatsApp. Lateness and absence notification protocols were also developed.

Fig. 5. The interior of the Huntington Avenue Five Guys Burgers and Fries [12].

From Fig. 5, food-related consequences such as four-person meals paid for by an offending party were utilized to ensure that people would be committed and respectful to the group's time. I found myself commonly in the role of the "recenterer" as project manager, as is outlined in our team contract, displayed in Appendix A. This does not mean that I had to commonly silence people who were talking over each other, but I had to get conversation back on track at times with phrases like "so how do we plan on doing ____." I had to do this at times when I was not project manager as well, and at other times I was the one who had to be recentered, but regardless I was part of the organization process.

Fortunately, we did not have significant enough disagreements about decisions to require group mediation sessions, in which we would have had to politely debate until a choice was unanimous. This is because we were generally allowed to explain ideas to each other in a thorough and convincing manner. Work was also held to the standard that all members must approve it by the time of submission. This was accomplished by requiring work to be shared an hour before the time it is due so that group members could peer-review work according to the rubric. After the project was called “boring” by our project mentor Chan, I collaborated with Joseph Durkin’s idea to make the exhibit into a Jeopardy-style game to successfully suggest that we turn the game into a contest between two users, so there is personal stake in trying to answer questions correctly. I later added the theme of The Incredibles vs. The Underminer and a narrative of a chase through an underground geothermal power plant in an IncrediDrill vehicle, requiring reenergizing, to make it appealing to children.

Fig. 6. The IncrediDrill, in all its glory.

From Fig. 6, one can see the 3D-printed IncrediDrill model adding to the exciting aesthetic of the physical model.

Another aesthetic principle I had insisted on and continually coaxed my teammates until they agreed was the concept of using actual water in the model. They had been initially hesitant due to catastrophic failures in previous years, but I assured them that this was the best way to make the exhibit’s teaching mechanisms as obvious as possible. I had spearheaded the poster with Joseph Durkin as well, iterating multiples phases of content development until it was as intuitive as possible.

1.4 ALTERNATIVES, EVALUATION AND EVOLUTION

In Milestone 1, we brainstormed potential project ideas. I led a discussion in which we thought up and categorized topic options on a whiteboard. After narrowing down to a final three, we wrote up pitches for projects that could teach each topic.

I developed a project idea involving geothermal energy, which ended up being our unanimous choice.

In Milestone 2, research was carried out to guide the design of an initial prototype drawing.

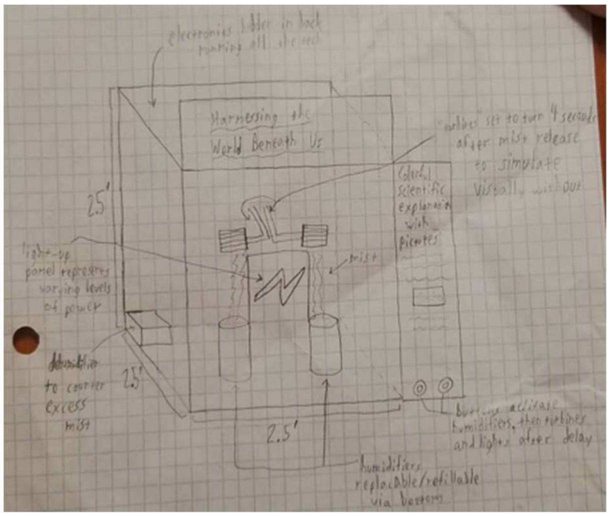

Fig. 7. The sketch of my initial concept drawing.

From Fig. 7, one can see the drawing displays a device that vaporizes water to turn one or two turbines, which would have lit up a light bulb at two different brightness settings to demonstrate that more steam results in more electricity. However, this idea overlooked any aspect of entertainment that would keep children users interested enough to stay and learn. Furthermore, the prototype only displayed one step of one process, completely overlooking the cyclical nature of geothermal processes.

The Kepner-Tregoe Decision Analysis resulted in us continuing John Chiaramonte's prototype with the lighting aspect of my concept. My drawing did third best in the analysis, scoring a 298 compared to a 323 and 362. It did better than Joseph Durkin's prototype due to his earning a NO GO status, losing it its candidacy.

For Milestone 3, I was responsible for the placing of the visual-only pieces on the top of the model to represent "above-ground" and "under-ground" and the insistence on the inclusion of real water. Both contributions were in the interest of the project goal of simple and realistic presentation, making the concepts easier to comprehend.

For Milestone 4, multiple important changes in both the theme of the project as well as the interactive component were made. Initial physical changes planned before the meeting with mentor TA Chan included making the overall design dimensions much smaller and less wasteful of physical space. The parts were all closer together this way and everything could be seen easily within the average frame of view. The other immediate preconceived change in the construction was to make the entire display window slanted at forty-five degrees to make the laptop screen, buttons, and other interactive parts all co-angular. Originally, the plan was to model how geothermal energy is used differently in different parts of the United States, with the user's interaction being limited to someone tapping a state, reading a blurb on how geothermal energy is used there, and watching the process be simulated with our power plant setup. While meeting with Chan, we learned that the user interaction component must be enhanced by making the display a game similar to Jeopardy or Family Feud, where two players could compete head to head answering questions about geothermal energy. To do this, we added a front panel with arcade buttons for buzzing in and a joystick for moving between answers (see the glamour shots of Appendix H). Because of this change in the interaction, we also decided that the theme would be broadened to be a simplified guide to geothermal energy's functions, and questions would deal with varying factors of the geothermal process. This contest game format would also benefit the project in the sense that the longer the interest of the users could be held, the more information can be passed on to them. I summarized the changes of this Milestone in a paragraph. Finally, I continued to develop a detailed SolidWorks assembly and diagram with the help of William Hodge.

1.5 FINAL DESIGN

Description

The final design is akin to an arcade trivia game, a two-person competition to answer questions about geothermal energy and its usage in order to geothermally power the Incredibles' IncrediDrill. The in-game narrative states that this IncrediDrill is needed to chase the villainous Underminer. All of which are characters that the young users would be aware of. Answers are input with a two buzzer and joystick system. Scores are tracked, and an end winner is announced to incite the kids' inherent interest in play. As questions progress, corresponding mechanical parts in the exhibit, visible in the glamour shots in Appendix H, are activated to help lead the users to the answer, while actively modeling both geothermal electricity generation and geothermal heating and cooling systems. Every question answered correctly by either player fills a progress meter, giving the game a teamwork and collaboration aspect; incorrect answers do not fill the meter, and those questions are revisited later to help show improvement and learning by the users. In this sense, players must genuinely try to answer all questions correctly to win the game. By making geothermal energy fun and positively reinforcing the invocation in the poster, we achieve our goal of promoting sustainability through the specific model of geothermal energy.

The project both simplistically and realistically models an actual geothermal plant. It is also widely educationally accessible, containing visual graphics and lights, tactile/mechanical parts, experiential gameplay, and even auditory sounds such as a whirring turbine and gushing water that can help users understand the answers and over-arching themes.

Beta Testing Results

The evaluators, when soliciting feedback, had allowed the test users to play with the game without the former being present to prevent any influence they may have on results. The users, one an elementary school-aged child, one a parent of this child, and one a Northeastern freshman international politics student, had tested separately to minimize potential feedback interference on each other and were given a four-question questionnaire to get back the information of greatest utility. These questions and their responses are present in Appendix E. To improve the project with this feedback, the exhibit was painted with two coats and a cave graphic background was added to make it look more finished. Plans were created for the GUI to be edited to make the text more readable and to have each screen panel progress to the next sooner after the pressing of buttons.

Contributions

One of the skills our group mastered was distribution of tasks, so that all of us would contribute as equally as possible

In Milestone 5, I did more than a fair share of work, which was my own fault by taking on too much. Along with William Hodge, I painted the exhibit with paints I acquired and made critical physical adjustments to the exhibit to increase the obviousness of the steps in the geothermal process (specifically, repositioning the turbine and humidifier to be better vertically aligned and rerouting the tubing to indicate that after turning the turbine, steam condenses to be reused in the generation process). I had created a first draft of our display poster with the poster board I bought, using pictures and preliminary educational content covering subjects from sustainability to ethics to the actual nature of our topic. Furthermore, I massively revamped the SolidWorks diagram to add detail and accuracy to the actual model. The development of the Incredibles theme and narrative to bring youth interest to the exhibit had been my responsibilities, as well as the progress meter idea and recycling through questions for long-lasting comprehension. I also had 3D-printed the afore-mentioned IncrediDrill model to be placed in the exhibit to add to the immersion of the game experience. I consistently created Gantt charts every Milestone since the second one. Finally, I created preliminary labels for the parts of the exhibit and logged all changes to the physical model during this Milestone.

In Milestone 6, I filed and chamfered the edges and corners of the exhibit to make it less pointy or able to be printed. I reprinted the labels that had gotten destroyed during the last Milestone. I constructed a new box for the humidifier (Hodge made one for the motor), so that they could be better vertically aligned. We then repainted the exhibit with a second coat to cover up the reconstruction. Finally, Joseph Durkin and I spent a lot of time redoing the poster so that it was not nearly as wordy or difficult to comprehend, trying to write in a way that can be read flowingly.

In Milestone 7, essentially all my work was involved in finalizing the labels with lamination and the poster content, which was eventually graphically designed in Photoshop and printed on a plodder printer. I created a final version of the Incredibles-themed sustainability triangle and had the idea for the layout of the final poster, with electric generation overview on the left, heating-cooling on the right, and ethics/sustainability in the middle. Finally, when there was a last-minute crisis and John Chiaramonte could not figure out how to export the Photoshop file as a PDF to be printed, panic set in. I troubleshooted and found a solution online that allowed us to get the final product printed in time for the exposition.

Resources

The group narrowly remained under-budget thanks to thrifty location and dogged acquisition of tools, materials, and decorations. We borrowed items from Professor Schulte-Grahame and our peers. A total of $100 was spent to create our final project. Personally, I spent $19 in order to print the poster and gather the paints and the poster board that would be used, as can be seen in Appendix J; I plan on reimbursing members of my group to make up the difference between this value and a perfect share of the financial burden ($25). In total, I spent around 111 hours on this project, as shown in Appendix K.

1.6 CONCLUSION

Observations from Exhibition Day

The students were more interested in the project than I anticipated on Exhibition Day. I forgot how much influence tunnel-vision and hyper-focus can have on some young children.

Fig. 8. An enthralled preschooler attempts to harness the world beneath us.

In Figure 8, one child, who appeared too young to be in elementary school, played with our exhibit for just under ten minutes before leaving. He never got a single question correct, as he likely was too young to read, but what I did notice was his giddiness at the Incredibles appearing in the game and fascination with the moving parts, the exact response we wanted to evoke from all the users. We engendered fascination from all our users, and many of them played the game as it was meant to be played, a two-player game in which questions are supposed to be answered correctly. I asked some kids what they thought the exhibit was about and many stated that "geothermal is important to make energy," which is a diluted, but spot-on version of our intended ethical take-away. We received no questions regarding how to play the game, meaning that it was simplistic, and many kids were able to complete the game without diverting their attention, indicating that the exhibit was entertaining and intriguing.

Reflections on Learning

I had learned a lot about the actual subject matter of geothermal energy, its forms and plants, and society's utilization (or lack of utilization) of this potential to a point that I now have a thorough understanding of this renewable energy source. The degree to which we were given managerial rights and relative creative freedom was a new and frankly, liberating experience for me that allowed me to work contentedly without inhibitions and a sense of autonomy. I had to teach myself woodworking techniques and efficient selection and usage of hand tools in order to contribute on "build days." I also had to teach myself many new SolidWorks tricks and tactics in order to make an accurately detailed CAD drawing of our exhibit at each phase. Subsequently, my fascination with the SolidWorks program has led to me becoming fairly adept at using this software, for which I am proud as a novice engineer. The methods I had learned to ignite and nurse creativity through the Top Hat readings and hands-on design activities have given me capabilities and confidence in design and problem-solving that will be integral to any work I do as an engineer.

Reflections on Working in a Team

This Cornerstone project has changed the way I approach teamwork. I've worked on teams before both as a leader and a member but had never operated in one that has this level of stress and rapid adaptation to challenges involved. It was important to never allow myself to be overwhelmed in a way that would disrupt group progress or be disrespectful to my partners. I have also had to learn entire skillsets in short periods of time in order to rise to the requirements of this group effort. From coding, to design, to physical construction, to problem-solving, I have been pushed to not just learn MATLAB, SolidWorks, and Value Sensitive Design, but more importantly, the ability to effectively teach myself new instruments like these. In terms of teamwork weaknesses, I primarily should have been more prompt. Doing work by the agreed upon times was one thing, but allowing for ample time for its peer review, discussion and reparation of faults was the ideal situation for teamwork that is respectful of people's time, trust, and anxiety-levels. I could also communicate more frequently on mobile messaging applications, as I often have not participated in or even been aware of WhatsApp conversations until sometime after the main discussion. This could be improved by checking my phone more often in general and reminding myself to leave my notifications ringer on via regular alarms so that I do not miss a messaging period due to a silenced ringer.

I think this project did truly allow my leadership skills and years of leadership training to come into practice. One of the best strategies I've learned when it comes to leading in small groups is to lead without making it clear that you're leading. A large group is different and requires a singular face to condense the goals of the assembly. However, in a group like the Cornerstone groups we were placed in, there was no need for a figurehead type or petty ego games that can be associated with trying to lead a few people. I try not to tell anyone to do anything as much as I try to lead the divvying up of tasks as a group and separating with our evenly balanced tasks. A quote I admire, paraphrased, is "the failure of a group is never the group's fault, but the leader's, and the success of a leader is never the leader's success, but the group's." The point of leadership, in my opinion, is not to lead, but to help other people gather and work to achieve their goals. Thus, I tend to primarily lead by example. I have not tried to have people come up with ideas or do work for me. I have tried to develop my own solutions that could help the group. I have taken strides to gather my thoughts and present the idea the best I could. If they collectively did not like it, that was my failure and we would continue with their ideas. If they had thought my idea was better by merit, then the group would continue with a good idea, one step closer to the target. I also have tried to be our group's energy source, jumpstarting lulls and stressed, tired moments with enthusiasm and jokes and starting the discussion of the next steps we need to carry out.

Conversely, my ability to be managed required some improvement. Proper management can balance speaking to and listening to fellow people. I am perfectly content being given tasks and actively attempt to keep my ego out of group activity. Bossiness was never something the group had to deal with that would result in negative reactions to management in the first place. In my desire to add value to the group's efforts and not under-contribute, I would occasionally over-contribute instead, taking on more than I could handle for several Milestones, requiring more of myself than I was reasonably able to learn and accomplish in the time allotted. At a couple points, this has resulted in less busy members to take on small amounts of my work in the latter half of the Milestone so that I could finish in time without sacrificing work quality. This was shortsighted on my part, and something I actively had tried to improve as the overall project progressed. In the final two Milestones, I felt that I have taken on an equal share of the work without feeling guilty, like I was not providing enough or taking on so much that I would have to hand off work to a teammate last-minute.

In cases that required overcoming adversities, we faced each issue by gathering together and problem-solving in the same room in conversation and communal visual diagram. We would use a method similar to problem definition in order to resolve it. First, we would identify what and where the obstacle was, most often by using the SolidWorks drawing of the model or the code to create a whiteboard sketch. Then, we could draw potential ameliorations on the board by passing the marker around to either adjust factors like object position or draw new solutions that would require new parts or systems. Essentially, we would have multi-phase brainstorming/brainwriting sessions. It is vital to note that no individual problem-solving was allowed so that no one was left out of the discussion. If one or more members could not be present for the "solution sessions," every decision, major or minor, would be communicated to them for approval before continuing so that we could minimize the chances of overlooking a flaw in the adjustments or new designs. Everyone had to agree on the new plan before it could be enacted.

The biggest asset to our team, in my opinion, was our humorous and fun personalities. We consistently dealt with the stresses of long work-nights and interpersonal disagreements with jokes and lighthearted teasing.

Fig. 8. The team and a spaghetti-loving Chan enjoying a dinner together.

From Fig. 6, one can see that sense of humor, when not aggressively intended, is a great reliever of tension, functioning like a pin popping a balloon. Our joking jabs at each other or life in general functioned both as invocations to get back to work or simple tactics of idea communication, while creating an environment of comradery.

1.7 RECOMMENDATIONS

If I could return to the beginning of the semester and start afresh, I would have planned my time to better plan for my difficulties or failures. The ideal scheduling of work should allow an entire extra day before a Milestone completion date for final edits and repairs for problems that have arisen. Much like any coding or CAD assignment, this extra time is helpful for fixing last-minute problems that would otherwise result in a stressful time crunch, decreased quality and functionality in the project, or actual lateness. Some of our submissions for this project were cut rather close. In these cases, work would have been much less troubling and even enjoyable if an entire extra day had been left over to put finishing touches on and review work. Given extra time, some additions I would have liked to include in this project are video displays and graphics to accompany each question that visually show how the processes modeled in the exhibit work. I also wish the group had had the time to acquire and set up lights to allow tubing to glow as the turbine turns to respectfully signify electrical generation and hot/cold water in the pipes in a water heat transfer by conduction.

WILL HODGE

2.1 INTRODUCTION

PROBLEM STATEMENT

Most Americans do not have a genuine grasp of the different sources of alternative energy that exist, especially ones that have not been fully adopted by the public. The options that exist to teach people about these types of renewable energy are often not easily accessible to children. However, alternative energies can be harnessed in more environmentally friendly ways than more mainstream energies and should thus be taught more to the public—namely the younger generation that will one day be leading society. Certain forms of sustainable alternative energy are rather obscure. One such example is geothermal energy, a form of alternative energy that utilizes the heat of the earth to create energy. Our problem was to design a museum exhibit aimed at children that teaches the concept of geothermal energy, how it is produced, and its uses in different environments in a fun, engaging way.

INTENDED BENEFICIARIES

Our beneficiaries include our clients, who in this case are Professor Schulte, the Northeastern team of judges, and the Museum of Science, and our intended audience, who are people, primarily children, old enough to read at a 3rd or 4th grade level at least. This means that the exhibit is probably best suited for 4th graders and up, since "43 percent of Massachusetts third graders are not proficient in reading" [13]. We designed for students (or any people) who have no knowledge or a limited knowledge of how geothermal energy works.

SUSTAINABILITY IN ENGINEERING

Without sustainability in design, the natural resources of the Earth would quickly be depleted, and the Earth would be put at great risk. Humans must find a way to meet their needs without compromising the ability of future generations to meet their own needs. Engineers must design solutions to problems with the triple bottom line in mind- the people/culture must be happy with the solution, it must be good for the planet, e.g. it should benefit the health of humans and not hurt the earth or its natural resources, and it must not be unnecessarily expensive. Engineers should also design solutions ethically. They should consider the needs of all users, including those who are disadvantaged. For example, an engineer designing a set of stairs for a building should keep wheelchair users in mind. This is known as value sensitive design. Anyone who uses a product, regardless of any disabilities they may have, should be able to use that product as effectively as someone without disabilities. We tried to incorporate ethical design into our project by implementing Universal Design principles, which are discussed in section 2.2.

PROJECT OBJECTIVES

The objectives of the project are mainly to teach children about the functionality and different applications of geothermal energy. We also hope to encourage information retention. The exhibit should also be engaging and fun for its users.

The exhibit's intended functions are to be a working two-player quiz game with button and joystick input. Our design also features an interactive model of geothermal energy production, which should have a functioning water loop, steam machine, and spinning turbine, all controlled by Arduino. These Arduino components will be programmed through MATLAB, connected to the Arduino program.

The constraints of the project have not changed much since the beginning of the semester. We are still working within a $100 budget, with limited time (around 2 months from start to finish). Also, the project cannot be too big or heavy, and must be easy to transport from Northeastern University to the Museum of Science.

2.2 BACKGROUND

RESEARCH

For Milestone 2 of this project, I conducted in-depth research about geothermal energy and models of the electricity production process. Researching this project was interesting for me because I, like most Americans, did not know much about geothermal energy. I mainly focused on the simplest form of geothermal energy and how the physical process of energy production works, compiling over ten sources about these topics. I found that the essential parts of geothermal energy production are an underground temperature hot enough to turn water into steam (at least 220 degrees Fahrenheit [14]), a turbine connected to a generator, and a network of tubes or channels for steam and water to travel through. All these components are included in our final design.

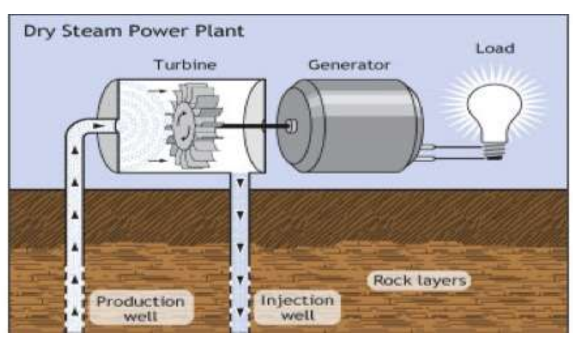

Fig. 9. The image I based my first design on. It depicts the basic geothermal energy cycle. [15]

The above image, which I found, ended up being the image that our team modeled the final geothermal energy demo after. In my research, I also found the small, USB powered steam machine that ended up in our final design. I also researched Roxbury Community College's geothermal plant and got one of my teammates into a Northeastern tour of the plant, which helped the group as we continued to research. Although, through my research, I found very specific and in-depth facts about geothermal energy, most of this information was not included in the project because we tried to focus on the most basic concepts relating to geothermal energy.

Ethics

The problem that our project contributes to addressing is that many Americans do not know about geothermal energy. This problem does not seem extremely significant at first glance, but if the next generation of Americans does not know about the best ways to produce energy, how can we expect them to make the right choices? Our exhibit introduces the concept of geothermal energy and stresses its sustainability, which we hope will get across the message to kids that geothermal energy is a great alternative to fossil fuels. With further development, this project could also be used to teach the concept of heating and cooling through convection (the transfer or heat or energy through a large mass of fluid particles), which would teach children both about an important use of geothermal heat and an important scientific principle.

If every person who interacted with the exhibit walked away with at least a basic understanding of how geothermal energy works, I would consider the project a success. However, certain steps must be taken once a project like this is completed in order for it to be successful. Once the design is finalized, it must be put in a location where as many people as possible can interact with it. In our case, the Museum of Science is a great venue to ensure that curious and open-minded people use the exhibit. To increase the likelihood that the project will teach users everything we want it to, questions could be further edited to make them as effective as possible. Alternatives to solving the original problem are teaching about geothermal energy in a classroom setting, making an educational video, making an online video game, or writing a book or magazine article about geothermal energy. By addressing the problem with an exhibit-type game, there is the possibility of kids only focusing on winning the game, therefore not actually retaining any information. To prevent this, we implemented a looping system where users must get every question right before they can end the game. Thus, every user will know the correct answers and reasoning for all questions by the end of the game.

UNIVERSAL DESIGN

According to the Universal Design website, "Universal Design is the design and composition of an environment so that it can be accessed, understood and used to the greatest extent possible by all people regardless of their age, size, ability or disability" [16]. In other words, Universal Design is all about designing solutions that work for everyone. It is important to ensure that those who are already disadvantaged are not further disadvantaged by their environment. Everyone should be on a level playing field at least. We incorporated many aspects of universal design into our project. All of the text on the poster is sized correctly and in the right type of font (the text is between 28 and 32 pt., and the font has no serifs). The screen is at a 60-degree angle, and the buttons and joystick are at a 45-degree angle. These angle measurements are both in agreement with the Universal Design specifications. When placed on a table of normal height, the exhibit is usable at both sitting and standing heights, which ensures that wheelchair users can use the exhibit.

2.3 METHODOLOGY & ORGANIZATION

As stated in the team contract, which can be found in Appendix A, the team split up work relatively evenly, mainly relying on the direction of the project manager for the first four milestones. We assigned jobs to each team member at the beginning of each milestone, although we sometimes took on some of our teammates' work if one task took longer than expected. The tasks that were completed each milestone can be seen in the master Gantt chart in Appendix I.

I was project manager for Milestone 2, which was when we really began to flesh out how we wanted our final project to look like. I scheduled a meeting with our mentor, Chan Le, and we all presented our ideas and decided on a final design. This milestone was when we started to figure out one another's strengths; we realized that John is very adept with programming and computer skills, Noah and I are good at creative design, and Joe is well suited for the written section of the milestones. This was also around the time in the semester when we realized how challenging Cornerstone is, and it reinforced the idea that scheduling and planning with a Gantt chart is very helpful. We almost could not meet with Chan because our schedules and his schedule were both so busy, so we tried to be better with time management from that point onwards.

After Milestone 2, although I was no longer project manager, I continued to help lead the team in certain ways. I helped organized a lot of our team meetings and was never late to a meeting. I tried to always be working when the group was together, in an effort to encourage my teammates to work as well. By the time we no longer had project managers (after Milestone 4), the team had grown close enough to organize ourselves without someone being in charge. We assigned tasks at the beginning of each milestone, and everyone worked until all work was complete.

2.4 ALTERNATIVES, EVALUATION AND EVOLUTION

For our first milestone, we came up with three main ideas for our project and decided between them. While composting and electric vehicles were close to being picked, the group ultimately landed on geothermal energy because we thought it was a topic that many people do not know about, and one that gave us a lot of creative freedom. For the next milestone, we all had to draw our idea of what the design should be.

Although the group did not choose my design after the Milestone 2 meeting, my original drawing is actually very similar to what our final design looks like.

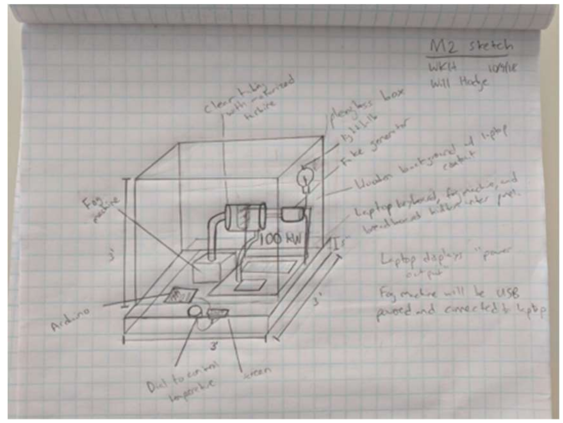

Fig. 10. A pencil drawing of my original design.

It includes the same steam machine, spinning turbine connected to a generator, and tubing loop that is visible in our final design. This final design is almost a mix of John's project and mine, although we picked John's. We took my box design with the bottom to hide the laptop and wiring and modified it to make it more arcade-esque. I wanted the whole box to be made of plexiglass, but we ended up using wood in our final design both because of cost and practicality. I did not include water in my design, as I originally thought that using real water would be too risky and challenging. However, when we started to implement our water loop, after Milestone 4, I realized that it could be done in a very clean way. Another big difference between my design and the final design is that my original concept was not a game at all. Users would simply turn a temperature dial and see how the system responded. We made a change after Milestone 3, after our second meeting with TA Chan. He reinforced the idea that the best way to ensure retention and interest from children is to make the exhibit competitive, so we decided to make our project a quiz game. We also altered the dimensions of the project after Milestone 3. The below image shows what the design looked like at the end of Milestone 3:

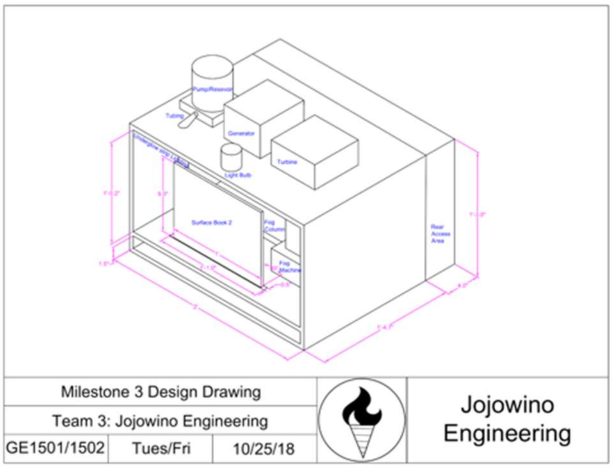

Fig. 11. An AutoCAD drawing of our design from the Milestone 3 document

Although the dimensions are hard to see, this shape was too boxy and large. At our Milestone 3 presentation, where we presented a cardboard model of the exhibit, Professor Schulte pointed out that users would not be able to see inside the exhibit from the sides. I then had the idea to slope the sides, which made the exhibit look more like an arcade game. We also scaled the exhibit down to make it easier to transport and to cut material costs. By Milestone 4, we had our final wooden shape, although smaller details were of course altered in the later milestones.

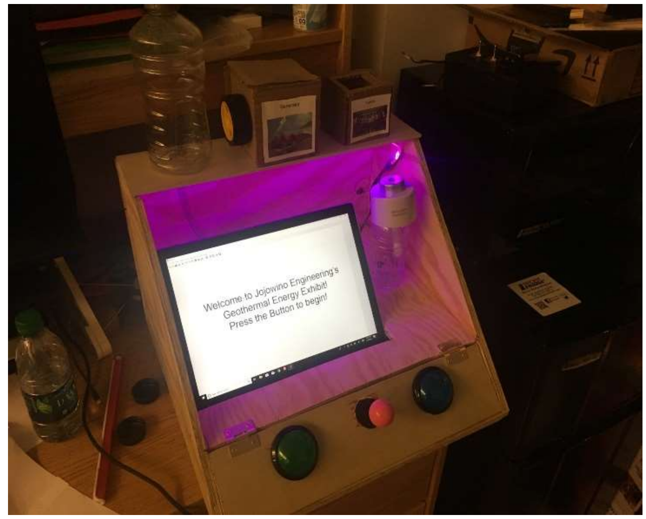

Fig. 12. Our finished product at the end of Milestone 4

2.5 FINAL DESIGN

DESCRIPTION

Since I wrote the descriptive write up for the Museum of Science for Milestone 5, I will include it here:

We designed an interactive game with the objective of teaching users about geothermal energy production. The exhibit is shaped similarly to an arcade game, with two large buttons and a joystick at the bottom. The buttons and joystick are placed at a 45-degree angle to the horizontal to comply with Universal Design standards. Since the exhibit is focused on geothermal energy, the exhibit has an "underground" section, in which a 12-inch screen will be placed, and an "above ground" section, which goes above the underground section. The exhibit is essentially an interactive 1v1 quiz game, where players will face each other and try to buzz in first, using the buttons, and answer multiple choice questions on the screen correctly. They will use the joystick to choose their answers. Since most users probably do not know much about geothermal energy, the questions are designed to teach about it as the game progresses. The exhibit features a complete, albeit very simplified, model of a geothermal energy production plant. A steam machine "underground," used to represent the steam produced underground, blows steam at an above-ground turbine, which then turns and "produces energy" with a generator. The exhibit also features a closed water loop, with which we will demonstrate the sustainability of geothermal energy. After the steam hits the turbine, a water pipe will run from just past the fan to an above ground reservoir. Then, the water in this reservoir will be pumped underground to the steam machine. This shows the fact that the water underground that is turned into steam is in a continuous cycle, with very little waste. The exhibit does not actually produce power, it just models geothermal energy production. We have also included green indicator LEDs on each of the components, so that if, for example, a question asks about the turbine, the user knows which part the turbine is. The quiz questions are all directly related to the model and require users to look at the model before answering. For example, one of the questions is "Where does the steam come from?" Users must look at the exhibit, see that the steam is coming from underground, and select the correct answer- to be specific, the correct answer is "Hot water underground." We believe that the combination of the model, with its moving parts and lights, and the competitive game, will both teach and entertain users. The exhibit is Incredibles themed, since we thought the character of The Underminer from the films fits in well with the underground section. The accompanying poster and graphical user interface for the game are both Incredibles themed.

Since writing that description, the team has added a feature where questions loop until every question has been answered correctly. We believe that this will help users retain information, as they actually have to get all the questions right to finish. The below picture shows the final project on the presentation day:

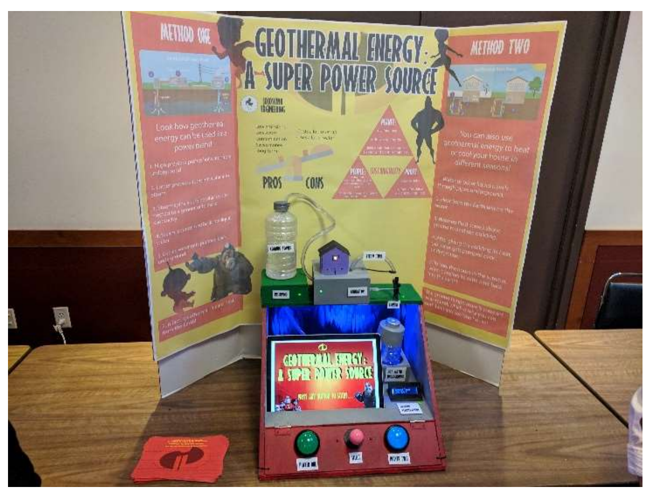

Fig. 13. The final project on presentation day

As can be seen in Figure 13, we also had to design a poster that educated users about geothermal energy. The challenge with this was choosing which information to include, as too much text makes the poster hard to read. While I was less involved with the poster design, I did help with the final aesthetics of the design, seen below:

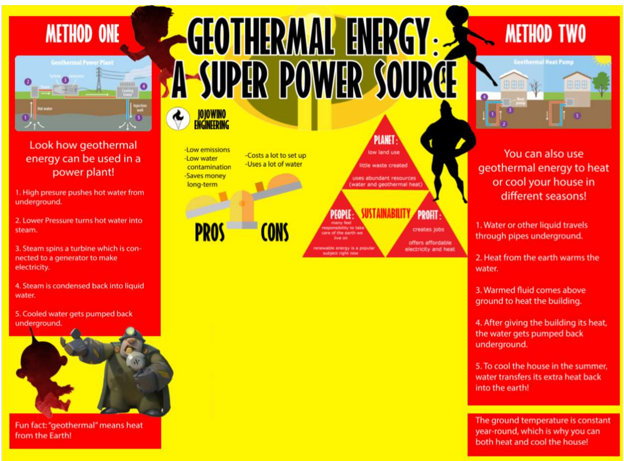

Fig. 14. The final poster design

At the very end of Milestone 7, right before presentation day, we decided to print out the entire poster on one sheet of paper using a plotter printer. This was a split-second decision, but it greatly improved the aesthetics of our poster.

Beta Testing Results

To beta test our project, we wrote the four questions that can be found in Appendix E and asked them of our three testers. These testers were my mother, my eleven-year-old brother, and my friend Kees from Northeastern. We concluded all testing before the end of Thanksgiving break, which gave us time to make any necessary changes for Milestone 6. Through testing, we learned that users learn what we want them to learn through using the project (the basic process of geothermal electricity production), which is a sign of success. We also learned that we needed to improve the readability of the GUI and clean up the overall appearance of the exhibit, which was useful information. Our testers also seemed to think that the exhibit was fun, which was reassuring.

Contributions

Although John Chiaramonte handled most of the coding and wiring for the project, I believe that I was the main person in charge of building our physical exhibit. Much of the nailing, sawing, gluing, sanding, etc. was done by me. I built most of the main box, many of the smaller boxes that held the Arduino components, the small house on top of the generator, and the hinged front of the exhibit which allowed for easier access to the wiring.

Fig. 15. A picture of me nailing the back of the frame to the rest of the exhibit

I did about half of the painting on the exhibit and was also very involved in the design changes that we made between Milestones 5 and 7. It was my idea to reroute our water pipe after Milestone 5 to simplify the project. The cave background, which is just an image printed on paper and glued to the back of the box, was also my idea. I also designed and created the entire GUI using GIMP, which took a significant amount of time and editing to improve readability and functionality. The entire GUI can be seen in the image log in Appendix H, pages 109-119. The turbine that we are using in our exhibit was designed and 3D printed by me:

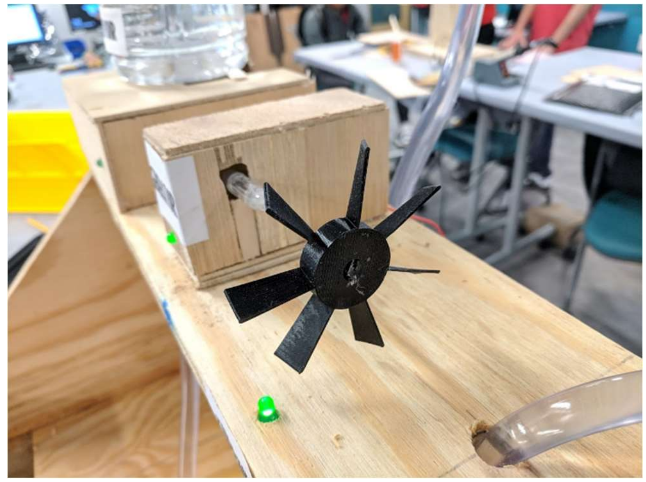

Fig. 16. The 3D printed turbine that I designed in our exhibit

I also wrote a large portion of the write-up for many of the milestones. Since John was preoccupied with coding most of the time, I ended up taking over some of the writing portions that we originally assigned to him. I also assisted Noah briefly with the first phase of the CAD model of our design, although he did most of that by himself. I was responsible for creating and updating the combined Budget/BOM every milestone(Appendix J). I also worked with my teammates to write the questions for the trivia game, which took a very long time because we wanted to ensure that our teaching goals were met through the small number of questions that we were limited to. To test whether we reached these teaching goals, I was the main force behind the preliminary testing of our product. I wrote the questions and solicited feedback from all testers. I then wrote the observations on their feedback, which can be found in Appendix E. It can be seen in Appendix K that I have the second most work hours logged out of the team, although the individual hour totals are very close.

Resources

Referring to the combined budget/BOM in appendix J, the team barely stayed within budget. I supplied the LED light strip, as I already owned one. I also took the hinges off my Redboard box to contribute to the project. My teammates bought all of the parts that we needed to buy, but I will reimburse them so that we all have paid an even amount for the project. In terms of time, I put many, many hours into this project. Looking at appendix K, one can see that I put in 113.5 hours individually, but everyone in the group probably worked more hours than were recorded.

2.6 CONCLUSION

Observations from Exhibition Day

For the most part, the guests at the Museum of Science like our exhibit and interacted with it in the way we intended them to. Most of the children who used our exhibit were a bit younger than we designed for, so the questions were a little difficult for them, but they were still able to answer them correctly with some guidance. Even children who could barely read interacted with the device; there was one small boy who stared at the water loop and turbine for about five minutes, saying nothing, which we thought was slightly funny. Adults liked our exhibit too, and they often participated in the experience with their kids. One man stopped by, saw that our exhibit was about geothermal energy, and talked to me about volcanoes for ten minutes. I actually learned a lot about the Yellowstone National Park volcano from him, which is an experience I wouldn't have had if we hadn't presented this project at the Museum of Science. Finally, the most positive experience our group had was with Greg, the Museum of Science employee who set this whole exhibition up. He really seemed to love our project and was very impressed with how well it taught the concepts of geothermal energy that we were trying to teach. Getting such positive feedback from an expert in the field was extremely gratifying for all of us and made me very proud of our work. All in all, most users really seemed to learn something from the exhibit, which was great to see. I believe that we reached all of our objective and goals with this project.

Fig. 17. A picture of me teaching Professor Schulte Grahame's son about our exhibit

Reflections on Learning

I learned a great deal from this project, both about myself and about topics within engineering. While I have done woodworking before, it has never been in conjunction with electronic components, so that was new to me. I learned a lot about electronics and wiring, such as how the Redboard works and how to solder. Also, I had to teach myself how to use GIMP to create the GUI, which took a pretty long time. I also taught myself new functions of Solidworks that we did not use in class to design the turbine. The new skills that I am most proud of, though, are my teamwork skills, which are discussed in the next section. I think that all the "people skills" that I learned while doing this project are the ones that will be most useful in the workforce. I can learn computer programs or carpentry skills whenever I want, but I do not always have the opportunity to practice working with a team that I do not know very well in stressful situations.

Reflections on Working in a Team

This project greatly improved my teamwork skills. In high school, whenever I had to work on a team, I would usually take over the whole project, or, rarely, let someone else take over the whole project. This was impossible with this assignment, because there was so much work and such limited time. Everyone had to contribute as close to an equal amount as possible. The challenge with this was getting everyone to work. Some members of the group were more active, in that they found out what needed to be done and did it, and other members of the group tended to need more direction. Learning how to get everyone to work, both as project manager and in the later milestones, was certainly a challenge for me. I think I still need to get better at communicating my negative feelings towards my teammates in a better way, as I tend to keep it inside instead of expressing myself. I think that I am good at organization when leading a group, as my stress keeps everything in order. I could be a little less passive of a leader, but I'll take that tradeoff if I continue to keep the morale of the group up. I think I'm pretty easy to manage- I do what I'm told when I'm told to do it, as long as I agree with the directions.

As a team, we overcame adversity mainly with humor. It was very stressful at times, but a well-timed joke or good-mannered roast always lightened the mood. I think my greatest assets to my team were my communication, as without good communication a project like this is impossible, my willingness to work, and my creativity in problem solving.

2.7 RECOMMENDATIONS

If I could go back to the beginning of the semester, I would have picked a topic that was much more specific. “Geothermal Energy” is such a broad topic, and throughout the course of the semester the team struggled with trying to condense a large amount of information into a small museum exhibit. I also think that we may have focused a little bit too much on the electronics and cool functions of the project, rather than on meeting our teaching objectives. Even if a project is the most technologically advanced exhibit ever, if it does not teach its content effectively it is not successful. If I had had more time, I would have liked to figure out a way to get the steam to go from the steam machine to the turbine through a clear tube. We tried this, but the water condensed inside the pipe, clogging up the steam machine. I would have liked to try to figure out a way to eliminate this condensation. Also, I would have tried to figure out a way to make the wiring more permanent, as right now wires tend to get disconnected from the breadboard, meaning that we have to take the breadboard out of the bottom of the exhibit and rewire it. I also would have made the water reservoir look nicer- right now it is a Powerade bottle, which we thought would look cool but ended up not really fitting with the aesthetics of the exhibit.

JOE DURKIN

3.1 INTRODUCTION

PROBLEM STATEMENT

Many sources of energy have not fully been adopted by the public, which results in many Americans not understanding much about renewable energy beyond a rather basic knowledge of perhaps solar and wind power. Other forms of alternative energy are thus rather obscure, such as geothermal energy. In fact, geothermal energy contributes the least to energy consumption out of all renewable energies [17]. Part of why geothermal energy is not as widespread stems from a lack of proper education in schools regarding renewable energy. Without this education from a young age, kids will not be as familiar to it later in life than many of the more widely used energies, such as petroleum, natural gas, and coal [17]. However, alternative energies can be harnessed in more environmentally friendly ways than more mainstream energies and should thus be taught more to the public—namely the younger generation that will one day be leading society. To work to rectify this, we will design a museum exhibit aimed at children that teaches the concept of geothermal energy, how it is produced, and its uses in different environments in a fun, engaging way that ensures retention and understanding while not losing the audience's interest.

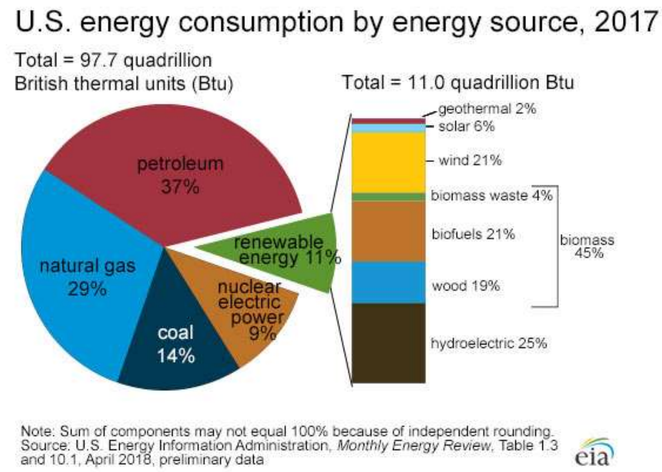

Fig. 18. A pie chart showing US energy consumption in 2018 and an additional bar graph showing how the use of renewable energy was distributed [17]

INTENDED BENEFICIARIES

Our intended beneficiaries for this design include both the more professional group of our clients as well as the more relaxed, casual group of users. Our clients include Professor Schulte-Grahame, her team of mentors, the Northeastern faculty members judging our design, and the Museum of Science. Our clients are the group who tasked us with creating a design, and they will be the ones who evaluate our design based on their knowledge of engineering and appealing to specific demographics. Our users include the museumgoers at the Museum of Science, mainly children, who will be interacting with our exhibit. These children are the group we intend to educate the most with our exhibit. Because our primary users are children, our project should be designed for an audience with a limited knowledge both on geothermal energy and sustainability. Going by Common Core standards, it is very unlikely that many kids will have been exposed to the concept of renewable energy on a conceptual level, as most early science standards focus on being able to read and comprehend scientific texts over learning scientific concepts [18]. As a result, we should design our exhibit assuming that any person who walks up to our display has little to no prior knowledge of geothermal energy or renewable energy in general.

SUSTAINABILITY IN ENGINEERING

According to the Environmental Protection Agency, sustainability is "meet[ing] the needs of today without compromising the ability of future generations to meet their own needs" [19]. Sustainability is necessary in engineering because, in order for designs to truly bring about some change, they must be able to last without severely infringing on those who use it, the economy, and the planet. Sustainable designs can enhance all three of these fields—which comprise a concept known as the "triple bottom line"—both in the present and in the future. The triple bottom line, also known as the three P's, evaluates how sustainable a design is by analyzing how it fits into our culture (people), how it uses natural resources (planet), and how it influences the economy (profit). For people, a more sustainable idea would be one that, for instance, improves the overall standard of living or gives everyone an equal chance to take advantage of the opportunities created by the design. In terms of planet, a sustainable design could utilize more renewable resources or reduce pollution. A sustainable design that appeals to profit could be one that stimulates economic growth or spurs the growth of several business fields. Sustainability in engineering also incorporates ethics and value sensitive design into its meaning. Ethically, engineers have a professional obligation to promote sustainability, most directly shown in the first Fundamental Cannon set forth by the National Society of Professional Engineers: "Hold paramount the safety, health, and welfare of the public" [20]. Designing products while keeping these three things in mind encourages sustainable design, as the safety, health, and welfare of the public are closely tied to cultural values, the planet, and economic growth. Value sensitive design, defined by the Handbook of Computer and Information Ethics as "a theoretically grounded approach to the design of technology that accounts for human values in a principled and comprehensive manner throughout the design process" [21], given its meaning, also adheres to sustainability. A large portion of people find protecting the environment and improving the standard of living to be of the utmost importance, so sustainable projects coincide with the values that many people prioritize. We were able to apply these concepts to our theme of geothermal energy, which is shown below with this homemade visual:

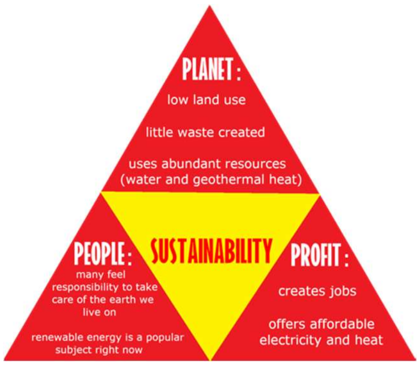

Fig. 19. Our sustainability graphic demonstrating the benefits of geothermal energy

PROJECT OBJECTIVES

One of our most important design objectives with this project is that it effectively shows any museumgoers how geothermal energy works and its uses. We want this exhibit to show that geothermal energy is both sustainable and practical. Another design objective in this project is that our exhibit is both engaging and informative for the museumgoers. In doing this, we can make sure people will actually take away the message of our project, which we believe can best be fulfilled by keeping the users interested. To keep users interested, we want to incorporate an interactive component of our exhibit in the form of a 2-player, Jeopardy-style quiz about geothermal energy. Our intent is that the combination of our model of how geothermal energy works coupled with the competitive nature of the quiz will keep users engaged and make them want to learn.

To accomplish these objectives, our main design function is that our exhibit is able to appropriately model a geothermal power plant. More specifically, it should be able to show that geothermal energy is sustainable and practical (per one of our design objectives) through the use of a working water loop, which demonstrates that the water being used to generate geothermal energy can be injected back into the ground and reused. Additionally, it should show how the process works by using a bottle cap humidifier and a 3D-printed turbine connected to a motor to simulate steam spinning a turbine. Finally, to catch users' attention, the power plant model has strategically placed LEDs at the different components of the plant to both draw users to relevant pieces for certain questions and to demonstrate processes like the generation of electricity and heating and cooling. To fulfill the objective of the exhibit being engaging for the users, the exhibit has a 2-player competitive (yet also collaborative) quiz game that requires them to look at the power plant model and the poster in order to answer questions about the process of generating and using geothermal energy based on their observations. The quiz uses a fake GUI in MATLAB along to progress through each question until the players answer them all correctly.

When this project was first introduced, we also received multiple constraints for what we can and cannot do. Conceptually, our exhibit had to incorporate some components from our smaller assignments, namely SparkFun wiring, MATLAB code with a real or fake GUI, and a 3D-printed piece made in SolidWorks. These features didn't provide too much trouble, as we were very used to using them from the assignments and were able to use them to greatly enhance our exhibit. We also had to include secondary components to the exhibit, including a poster and a handout. While these resources weren't too difficult in and of themselves, they did require us to step away from the physical exhibit at times so we could ensure they were of just as high quality. With practicality, we had to ensure that we stayed under a $100 budget set by Professor Schulte and that our project could be easily transported. In order to do this, we had to make the exhibit compact enough to be easily carried and to fit onto a table to be displayed. These constraints weren't difficult to satisfy. In actuality, they made it easier to construct because we realized that making the exhibit smaller would both save time and be more convenient for us to move, and the overall price of construction was reasonable when split between the four of us. Finally, the constraints in time came mainly in the form of the Milestones and what we needed to accomplish by each one. Because each Milestone had different requirements, we had to devote our attention to different aspects of the project rather than work on what we wanted to at any given time. Additionally, the Milestones coupled with the sheer amount of work pushed into one semester required us to work fast and always be aware of how much we needed to get done by the due dates.

3.2 BACKGROUND

RESEARCH

While doing research for the project, I focused heavily on the different ways geothermal energy can be generated. I found out that there are three main methods of producing electricity in a geothermal power plant—dry steam, flash steam, and binary cycle [22]. A dry steam plant harnesses energy by taking water vapor directly from the ground, meaning the water is already in a gaseous state by the time it is extracted. A flash steam plant, on the other hand, extracts hot water from the ground and vaporizes it directly in the plant. Binary cycle plants act very differently—they create steam by using hot water to heat up another fluid that has a lower boiling point than water, allowing steam to be created faster. One main advantage to this process is that it allows the water to be at a lower temperature, since the water itself isn't going to be boiled. However, for this project, I decided it would probably be best to focus on comparing just dry and flash steam plants because they are easily comparable and it keeps the project simpler. The differences between dry and flash steam plants described above can be visualized with the two figures below:

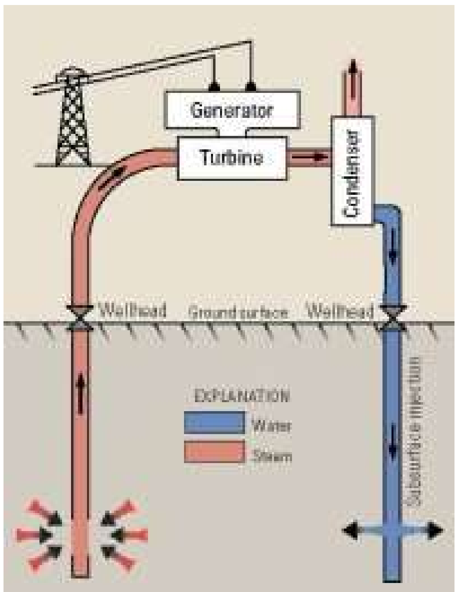

Fig. 20. A dry steam geothermal power plant [22].

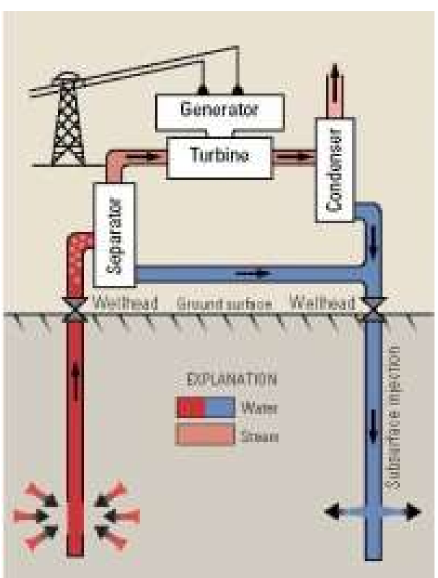

Fig. 21. A flash steam power plant [22].

Our exhibit was made to model a flash steam power plant, as indicated by the addition of "hot water underground" as a label in our exhibit.

In addition to researching the different methods of generating geothermal energy, I also researched the different ways geothermal energy can be used, namely comparing geothermal power plants and geothermal heat pumps [23]. With a power plant, the steam or hot water (depending on the type of plant) is pumped from the ground into the plant. If this is a flash steam plant, the hot water is then vaporized into steam after moving from high pressure to low pressure. At this point, the steam turns a turbine connected to a generator, which produces electricity. The steam is then cooled and injected back into the ground as water. This process of using geothermal energy to generate electricity is seen as an "indirect" method. Alternatively, using a geothermal heat pump is seen as a more "direct" use of geothermal energy. In this process, water moves through a series of pipes connected to a heat pump to either heat or cool your house depending on the weather. When it is cold outside, the water heats up underground and transfers this heat into the building once it is aboveground. The cold water gets pumped back into the ground to repeat the process. When it is hot out, the water can cool the building by absorbing the heat and then transferring it into the ground when it is pumped back underground. Our exhibit is designed in such a way that we can effectively model both uses depending on the question being asked. The comparison between the two uses of geothermal energy can be seen below:

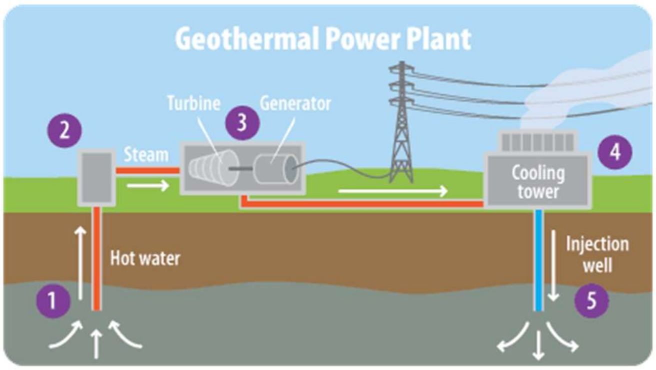

Fig. 22. How a geothermal power plant produces electricity [23]

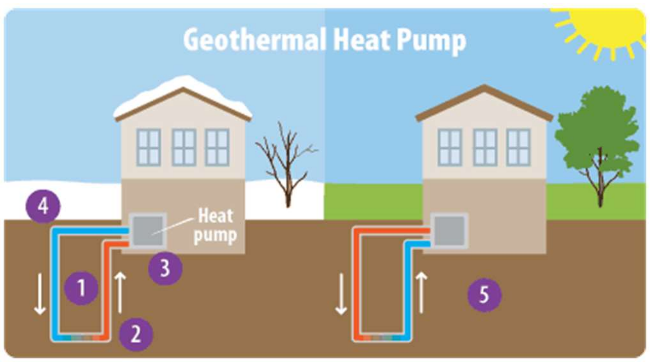

Fig. 23. How a geothermal heat pump heats and cools buildings [23]

Ethics

We designed our project to address the lack of exposure that some forms of renewable get, and we decided to pick one form as our main focus—geothermal energy. We believe that, given the necessity for renewable energy and the lack of exposure that some forms get—especially in terms of educating young children—this is a very significant issue that, if left unsolved, could harm our planet in the future. By showing young kids another form of renewable energy, we would expose them to the concept and importance of integrating renewable energy into the world—ideas that they can carry on into their later years and potentially study and implement. In addition to our proposed problem statement, this project can also address wider issues, such as those covered by the triple bottom line of sustainability. If this level of success is reached, we could see multiple forms of renewable energy being more common and affordable because more adults will be studying these ideas. We could see a cleaner Earth as a result of less pollution and more renewable resources being used, a booming economy because of the growth of cheap renewable energy, and an increased standard of living from both the increase in clean energy and the affordability of renewable energy. However, thinking more realistically, this project would be a success if kids can walk away from our exhibit with more knowledge about renewable energy and understand not only how processes like geothermal energy work but also why they are valuable to help preserving our planet.

In order for the technology to actually address the problem, it will need to be exposed to its target groups in order to pass the information along. In our case, the first target group our exhibit reaches is the visitors to the judged gallery walk, where engineering students and professors were able to see and interact with our exhibit. The second target group the exhibit reaches is the patrons of the Museum of Science. These target groups will have to read and interact with our exhibit in order for us to address our problem statement, as this is how they will learn more about geothermal energy and its importance. To increase the likelihood that this exhibit accomplishes this objective, we can make it more engaging and user-friendly, so that the entire display seems more inviting to anyone who walks by and makes them want to come look at it. The inclusion of a clearly recognizable, fun theme and an interactive game can accomplish this. These components would catch people's attention because it would introduce them to the concept using a theme that they're familiar and comfortable with and allows them to test their knowledge with the game to prove that they do understand what they're learning. Additionally, the project should also be educationally accessible to a large number of people so that most, if not all, of the people who interact with our exhibit can understand the information we present them with. To do so, we can adhere to the guidelines of universal design so we know how to best construct our project for the visitors.

Considering other options that are less technologically sophisticated, one that quickly comes to mind is that educators could put forth the effort to heavily incorporate education about geothermal energy or even just general renewable energy into elementary and middle school science classes. Emphasizing renewable energy in these classes as opposed to making them merely one quick lesson or unit would allow kids to better retain the information and actually understand why renewable energy needs to be talked about. To maximize effectiveness, education on renewable energy should span beyond memorizing facts and figures, something most elementary and middle school science classes focus on. Rather, any education on this topic should discuss its present relevance and why it is necessary for the future, perhaps even requiring the kids to consider their own methods of implementing renewable energy into the world as a way to test understanding. For this method to be successful, schools would need to put in the time and money to developing a more renewable energy-friendly curriculum and perhaps to hiring teachers with backgrounds in studying renewable energies.

As with any design, this approach runs the risk of the target audience not being interested in the information and, therefore, apathetic to the larger issue. With the alternative approach outlined above, this apathy can come from multiple sources, including the school directors in charge of funding and creating the curricula, the teachers put in charge of teaching the material, and the kids who have to learn the material. If even one of those three groups does not deem the subject important enough, renewable energy's value in the world will not come across as clearly enough, and the movement to make it more prevalent will stagnate. The fullest efforts of all three groups are required in order for this approach to truly make a difference. With our exhibit, kids could easily become disinterested because they care more about the theme or watching the physical components of the exhibit behave as opposed to learning from the interactive portion. As a result, they could easily cycle through all of our questions just to watch the exhibit do different things without getting any value out of the subject. To rectify this, the quiz can be designed to ensure that the kids don't complete their experience with our exhibit by having the quiz play until all questions are answered correctly.

Universal Design

According to the Center for Universal Design, universal design is "[t]he design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design" [24]. Quickly summarized, this means that an exhibit made with universal design in mind will allow all people who view it to use it, regardless of physical factors such as height, vision, or physical disability. Making an exhibit that follows the guidelines of universal design is important because it ensures that a wide array of people will be able to interact with the exhibit and learn from it. On any given day, a designer doesn't know what kinds of people will interact with an exhibit, so incorporating universal design is important in the inclusion of groups with different sizes, learning styles, sets of knowledge, and physical abilities.

When creating our exhibit, we paid careful attention to incorporating universal design both into our interactive display and the poster board. The biggest focal point of the interactive portion—the Surface Book—sits at a 60° angle with respect to the table, allowing the most people to easily see it when taking the quiz. The buttons and the joystick are at a 45° angle with the table. Our poster board also satisfies universal design. All of the major text is either 28pt or 32pt, excluding only the text present in images. In addition, none of the text is bolded, capitalized, or hyphenated. This way, we can ensure readability from a reasonable distance without having too many text effects that would distract from the information.

3.3 METHODOLOGY & ORGANIZATION

While I was project manager, I wanted to adhere to the quality of work guidelines set forth in our team contract, which can be seen in Appendix A. With each Milestone, we wanted to produce the highest quality work that we possibly could and merely wanted the project manager to act as a facilitator rather than a micromanager. I believe I accomplished this task in my ability to simply delegate jobs and then trust that everyone in the group will produce quality work and that we can hold ourselves accountable for the work we have to do. Since my Milestone focused heavily on construction, I was very proud of my group for being able to take some direction and use it to produce what was, in my opinion, a great first iteration, shown below:

Fig. 24. The first iteration, a prototype made out of cardboard

Even though there was still much to be improved upon, I thought we established a solid foundation and began to realize what we would need to fix in the future, which gave us good direction for later iterations.

I acted as project manager for Milestone 3—the Milestone where we built our first prototype out of cardboard. During this Milestone, we got our first glimpse of just how much space our initial idea took up. Once we started constructing, we agreed that the project would have to be much smaller but decided to use the current size for this Milestone for the sake of authenticity. As we built, we took note of some design ideas that we liked, such as the positioning of the power plant components and the laptop to model the aboveground and the underground components of a geothermal power plant, the raised lip of the whole display that left space underneath, and the positioning of the laptop on the left side of the project. All of these design ideas remained in our future iterations and can be seen in our final design—with slight modifications. Because we had reached a point where we began to understand each other's strengths, we realized that we could make great progress in regard to functionality. As a result, by the time the Milestone 3 Town Hall happened, we made great strides with developing an interactive aspect of the project. I believe that having this early foundation for code allowed us to make the alterations we wanted to, which ultimately gave us the interface for the final design.

Looking at the large Gantt chart in Appendix I, one can see that scheduling became incredibly important around the time of Milestone 3, denoted by the yellow blocks in the chart. This Milestone marked the first time where we had to devote significant time to an aspect of the Milestone, with the prototype construction requiring three days to complete. Because of the time needed here, we began to realize that it is not necessary for all four of us to meet as a group every time we have to work on the project. Because some people had classes or other obligations, we tended to come and go from FYELIC as we found free time and attempted to devote an equal amount of time between the four of us. However, we still found it important to meet as a whole group at least once or twice, which required us to pay careful attention to scheduling as the pace of the semester increased. Meeting as a whole group was important to us because it helped us ensure that we were all satisfied with our progress and the finished product and made it easier to have discussions about our opinions and ideas.

3.4 ALTERNATIVES, EVALUATION AND EVOLUTION

During Milestone 1, we had our first group meeting where we discussed the direction we wanted to take with our project, allowing all members of the group to shout out any ideas they came across that they felt we could thoroughly explore for the whole semester. This process primarily consisted of researching topics and proposing any interesting ideas, followed by a discussion over the proposed topics to find one that we all liked. We had to narrow down all of our ideas to three finalists, and none of my ideas ended up reaching this final stage.

In Milestone 2, we each had to create our own prototype for a possible direction the project could take. As I stated above, much of my research centered on the different ways geothermal energy can be produced. As a result, I thought it could be interesting to demonstrate those processes in our exhibit, which resulted in my prototype shown below:

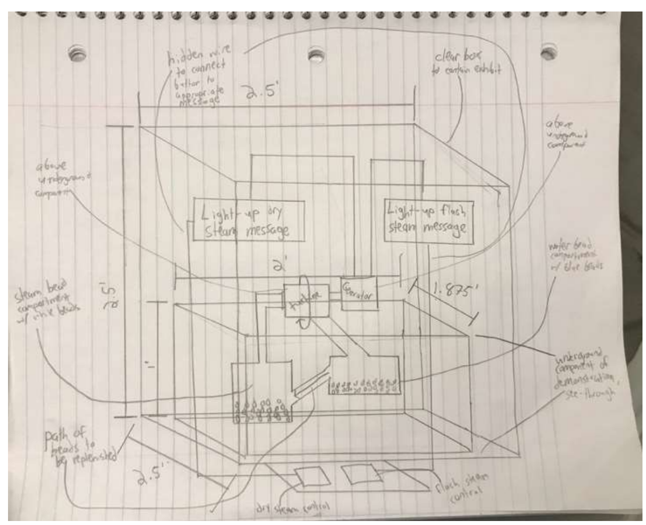

Fig. 25. My concept drawing for Milestone 2, showing the different processes for generating geothermal energy. After meeting with TA Chan, this idea was found to be not feasible.

Because of Professor Schulte's stories about how exhibits involving water have gone in the past, I aired on the side of caution and opted to use beads to represent water and steam as opposed to actual water. I wanted to implement two compartments into the design—one for steam beads and one for water beads—that would move beads throughout the exhibit to appropriately model two forms of geothermal energy production—dry steam and flash steam generation. However, my idea didn't make it through in the decision-making process because, according to our mentor Chan Le, constructing it would have required knowledge beyond the scope of the class. Ultimately, we selected John's concept drawing and used that as our initial blueprint for the exhibit.

In Milestone 3, we began our first iteration of the exhibit by making a cardboard prototype. Because this Milestone focused mainly on functionality and because cardboard is easy to work with, we were able to create a good initial GUI and set up our first major component of the final design—the humidifier. Because we decided to use a Surface Book to allow users to interact with the exhibit, we moved away from enclosing everything and instead opened the exhibit up. With this, we incorporated the idea of having two components of the exhibit, with an "underground" level to show where we harness the energy from and an "above ground" level to show how people can use the Earth's heat to generate the energy. However, in this Milestone, we also realized that our initial sizing ideas produced a rather cumbersome model, and we realized that this issue would only worsen once we built the exhibit out of wood. We noted this issue as something to rectify for the next Milestone. We also realized after receiving Town Hall feedback that this design severely limited visibility and accessibility only to people directly in front of the exhibit, which could turn away users who cannot get a good view of the project.

In Milestone 4, we used the feedback from the previous Town Hall to enhance the user experience with our exhibit. Some people felt that our interactive portion was too simplistic, so after hearing that feedback and having another meeting with TA Chan, we decided to incorporate a more competitive aspect into our project by using a joystick and buttons to create a Jeopardy-style quiz game, where the users would compete to answer questions about geothermal energy the fastest. We created three demo questions to show that we were taking a new direction with our project. Additionally, we rectified the size issue by significantly reducing the dimensions of the exhibit, making it much more portable and easier to manage, which also reduced the overall cost of materials. Finally, we made our first wooden prototype, establishing the skeleton that we would use for future iterations of the project.

3.5 FINAL DESIGN

DESCRIPTION

Fig. 26. The final product alongside our poster and handouts

Our final design is an encasement that is 16.5” tall x 20” deep x 21” wide. The front face is slanted at a 45° angle in accordance with universal design. The encasement has three major areas—the player board, the underground, and the above ground. The player board features two arcade buttons and a joystick. The buttons allow a player to navigate throughout the game, lock themselves in as the active player, and lock in an answer. The joystick lets players select their answer among the four possible answer choices for each question. This section of the exhibit is also connected to a “shelf” in the encasement by two hinges, which gives someone the ability to open up the player board section and look inside. This is where we decided to put our wiring, as it gives us easy access to make any adjustments we may need to make or resolve any wiring mishaps that may arise.

Above the player board, starting at the “shelf” mentioned above, is the underground component of our display. Next to the left edge is the Surface Book, which acts as the game screen where players look at and play the quiz on. This component is modeled after the inside of the Earth—where much of the heat is located—to clarify the idea of geothermal energy being created from this heat. Also inside of the underground component is a small box holding a hidden pump to move water through a closed water loop connected to the above ground and a small bottle filled with water that acted as a source for the humidifier, which modeled the creation of steam. This “steam” travels upwards to interact with components in the above ground.

The above ground component of the exhibit models a geothermal power plant. As the “steam” from the underground travels upwards, it appears to spin a turbine that is connected to a generator. In reality, this turbine is connected to a motor that allows it to spin. As the turbine spins, it appears to generate electricity by lighting up an LED on top of the generator. On the far left of the above ground is a water reservoir, made using a larger water bottle, that models the capturing of water after the steam condenses. The water in this reservoir gets injected back into the ground to repeat the geothermal process. In our exhibit, the water in the makeshift reservoir travels down a pipe connected to the pump in the underground, closing the water loop.

Our poster board provides background information on geothermal energy, specifically outlining the two ways geothermal energy can be used through power plants and heat pumps. Each method takes up one side fold of the poster, which allows each one to be large enough to capture people's attention and be easily read. The poster also includes information regarding how geothermal energy is sustainable in the form of a triangular graphic with three sections for each part of the triple bottom line. This graphic is placed in the center of the poster, making it one of the first things viewers would see. This placement helps emphasize the importance of sustainability because it introduces it immediately into the exhibit. Additionally, the poster also describes the ethics of geothermal energy to validate that it is, in fact, a useful form of energy. The whole poster also has Incredibles-related graphics to tie the theme into the information, as well as attract anyone who passes by. The whole poster was printed on one sheet of plotter paper, which is how we were able to include so much into the design.

The game component of the exhibit acts as a Jeopardy-style quiz, with the main idea having two players playing at once. However, it is also possible for one player to play against themselves and test their knowledge. The quiz, along with the encasement and poster, is themed after the Incredibles movies, specifically centering on the antagonist the Underminer. Every GUI image of the quiz has an Incredibles theme to appeal to the young demographic in the Museum of Science. The goal of the game is to correctly answer every question in order to fill up the power meter and fully charge the Incredi-Drill. Every time the user incorrectly answers a question, a screen will pop up displaying the correct answer and why it is correct. Additionally, all incorrect answers are asked again at the end of the game until the users get all of the correct answers. This feature is meant to solidify the user's learning experience and ensure that they take away the knowledge that we present them with.

Beta Testing Results

For our beta testing, we made sure to collect all feedback before Thanksgiving break so we would have enough time to sort through our results and plan any changes. We took advantage of having group members with family close to campus and got them to test our exhibit during a visit. Specifically, we had Will's younger brother try it out to satisfy the minor demographic and his mother to satisfy the Museum of Science patron demographic. Additionally, Will asked his friend Kees, a computer science and international affairs major, to test it out so we could satisfy the non-engineering student demographic. After each person interacted with the exhibit, we asked them four questions: “What do you think this exhibit was trying to teach you?”, “Rate how fun the experience was on a scale of 1-10”, “What was your favorite part of the exhibit?”, and “What was your least favorite part of the exhibit?”. A quick summary of the questions we asked and everyone’s answers can be found in Appendix E. To summarize, the overall reception of the exhibit was positive, with each person being able to correctly identify at least one concept that we intended to have the users learn. Additionally, when rating how much fun they had, our three users gave us scores that averaged to 9, an indication that our project will most likely be engaging and interesting for the users. Some of the most significant pieces of feedback we got came from Will’s mom and Kees. When asked what her favorite part of the exhibit was, Will’s mom said that she liked how we programmed the exhibit to act differently in different situations, citing the water “boiling” on command. Her assumption that the water was boiling was funny at the time and also let us know that we were on the right track with trying to closely model the actual process of generating geothermal power. Kees, on the other hand, felt like the exhibit as a whole looked unfinished. We thought we were on a good path to being done with the physical model at this time, so we used his feedback to try and find ways to improve the design and make it look cleaner and more professional.

Contributions

I believe that I kept myself rather flexible in terms of how I could contribute to the group, easily fitting into any role where I was needed and devoting my full attention to completing the task at hand diligently. I found myself running around Boston a lot for the sake of our project. Most notably, I took on the task of attending the Roxbury Geothermal Tour and taking notes on what was discussed so the group could possibly use that information to give us some direction with what we wanted to discuss in our project. One important aspect of the presentation the mention of their geothermal heat pump, an idea we had previously not considered too heavily. During the tour, we even got to look inside the room storing the actual pump and the pipes, which can be seen on the next page:

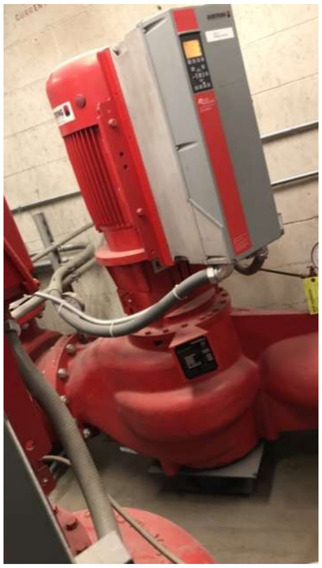

Fig. 27. An inside look at the geothermal heat pump room at Roxbury Community College

Greater knowledge of geothermal heat pumps allowed us to incorporate this method of geothermal energy more heavily into the project, resulting in our making the exhibit be able to model both a power plant as well as a heat pump and our inclusion of a question related to heating and cooling buildings using a heat pump.

I also devoted a lot of time to supplemental components of the project, namely the poster and the handout. I conducted a lot of research to find relevant, interesting content for people viewing our exhibit and designed both pieces to be eye-catching, but not too flashy. In terms of research, I designed three open-ended questions that would assess how much the readers took away from our exhibit and would show much they understood the content we provided. Additionally, I did further research into geothermal energy to provide readers with facts I put the handout through multiple iterations in order to find one that both appealed to our audience and didn't detract from the information. The first iteration was overly professional and focused solely on the information, which would have disengaged readers. With my second iteration, I heavily incorporated the Incredibles theme to make it more visually appealing while also retaining all of the important information. This second iteration ended up being very close to the final version, where only a couple small changes were made to improve readability and not overwhelm the readers. Finally, I volunteered to compile the final report, a rather time-consuming job given the requirements. I put everyone's individual write-ups into one master document and formatted all of the citations and figures and some of the appendices to ensure that they looked clean and professional. Because we would constantly edit portions to ensure the final product was perfect, this resulted in multiple save files of the reports and a lot of time spent ensuring that all of the information flowed well and remained consistent throughout the report.

Resources

Looking at Appendix J, our group managed to stay right on budget, spending approximately all of the $100 we were given as a limit To contribute to the materials used in our project, I went to the

Home Depot in the South End to get the majority of the wood we used for building (which cost approximately $33) and acquired waterproof silicon from Professor Schulte, which was useful in the construction of our water loop to help prevent leaks.

In Appendix K, you can see that I devoted a recorded 100.5 hours to this project. As a group, we agreed that all of our numbers were likely severe underestimates because we tended to estimate our times based on how long we believed some jobs should take, especially when we worked on pieces of the project individually and failed to pay attention to the time.

3.6 CONCLUSION

OBSERVATIONS FROM EXHIBITION DAY

While I watched the exhibit, I could see that the children who approached it were very entertained by the power plant we had set up and didn't even mind having to take a quiz in order to interact with the exhibit. They were so enthralled by the moving parts and quickly picked up on the fact that these pieces related to the question currently being asked. Once they saw that the exhibit changed depending on the questions, they were very excited to see how it changed with each question, which only got them more interested in the quiz, just like this kid above on the right:

Fig. 28. A curious child intently reads the question on the screen

One such visitor who stood out to me was a boy who was too young to read and asked me to read the questions to him. As we progressed through each question, he would carefully pay attention to the model to try and find the right answers, the gears in his mind almost visibly turning as he evaluated each answer. He would always proudly exclaim "Yay I got it right!" whenever he answered correctly. I could see that he was very excited, more because he got the question correct rather than because the exhibit was doing something different. By the end of the quiz, he excitedly reached out to grab a handout even though I hadn't even previously acknowledged them. Even after finishing, he stuck around and asked me to explain the pictures on our poster because he couldn't read them. Watching how interested he was in the topic and how much he liked just getting to learn the concept of geothermal energy made me very proud of our exhibit and the fact that kids enjoyed it not only for its moving parts and aesthetics, but also for its content.

After seeing real Museum of Science patrons interact with our exhibit, I can confidently say that I believe our exhibit successfully addressed our problem statement and met all of our objectives. Many of the kids who came up to our exhibit were excited to interact with it and actually took the quiz seriously as opposed to playing only for the sake of winning. They had fun not only playing the game, but also learning the concept of geothermal energy. Many adults also came up to our exhibit with an idea of what geothermal energy was but didn’t know much past that. This became evident as they played through the quiz and struggled about as much as the kids did. Watching how all the visitors played through the game and observed the exhibit showed me that everyone who came up to our display did manage to walk away with some newfound knowledge about geothermal energy and were able to see why it is a useful source of energy.

The best proof that our exhibit was a success, however, came in the form of affirmations from Greg, the Museum of Science employee who helped coordinate our exhibition day. He came up to our exhibit and talked with us at one point, praising us for our ability to make a fun exhibit that could also teach the users. He loved how we designed the exhibit to act differently depending on the question and how the questions challenged the users to find the correct answers based on how the exhibit changed. Listening to his excitement over our project made me feel very proud of all of the hard work my group and I put into the exhibit and removed any doubts that I may have had about whether or not we had accomplished our goals. Given the experience I know he has with designing museum exhibits, his positive feedback made me realize that we succeeded with this project.

REFLECTIONS ON LEARNING

Throughout this project, I learned both about a form of renewable energy I was previously unaware of and how to effectively work in a group on an engineering project. Before this project, I had never known much about geothermal energy. Working with this topic exposed me to a new form of energy and made me realize just how useful it can be to generating energy for our planet despite how little use it currently gets.

Because of this assignment, I also gained experience working on an engineering project. With all my previous experiences, I never had to do any kind of building or programming, so a large portion of what this project required was foreign to me. I had to learn about the most effective way to build a structure and what was required in order to keep it stable. I also learned about how much work was required to effectively program a GUI. Even though I didn't participate in the actual coding process, I wanted to be aware of the wiring and the coding because I am an electrical and computer engineering major. I think that participating in the design and building process, as well as keeping up with how the code evolved, taught me a lot of valuable information that I will carry with me into future classes and into future careers.

Reflections on Working in a Team

The most significant field where this project influenced my team working skills was in the fact that I had to learn how to take on less of a leadership role than I normally have in the past. When I did group projects in high school, I was used to leading everyone else and determining how a project would go because everyone wanted me to do that, as the "smart kid". However, with this group, everyone was used to being "the smart kid", so everyone's first instinct was to try and assume leadership. At first, I think we all wanted to take on such a role and prove ourselves to everyone else. This led to an early disconnect between the group members. Once we realized that we did not have to prove ourselves to each other, we grew closer as a team and saw that we all had our own strengths to contribute to the group. We held true to our team contract and respected each member's abilities and worked through our issues openly and in a constructive manner, which was highly beneficial for team morale. Additionally, we were able to tear down the initial walls of working with people who are still relatively strangers through our sense of humor throughout the process. With every meeting or building day, we would always find ways to incorporate humor into our work, usually directed at each other. Our willingness to joke with each other and show our true senses of humor demonstrates a closeness that formed between all of us, which allowed group settings to become very comfortable, promoting openness and trust between us.

I think that, if there is any aspect of teamwork I still need to work on, it would be communication. In my normal life, I tend to make decisions very quickly and rush into things. That habit translated into the group work. If I suddenly could not make a meeting for any reason, I sometimes forgot to inform my group because the reason came up at the last minute. Such poor communication skills can lead to confusion within the group and can create inconveniences, so I have tried my hardest to prevent these mistakes from happening.

I would say that my leadership style is one that provides direction while not overwhelming my fellow group members with questions and suggestions. I became the project manager at a point where each of us began falling into our roles, and we were getting more comfortable with each other. As project manager, I only wanted to make sure that everyone knew what they had to do and what we had to accomplish by the due date. Other than that, I didn't have to monitor my teammates to ensure that we would get the work done. I only had to lay the foundation, and everyone knew what to do afterwards. In terms of being led, I feel like I was agreeable in terms of receiving tasks. This willingness to fit into any role was possibly my greatest asset to the team. Coming into the project, I felt almost like a liability because I didn't have much of the engineering experience that other members had. However, I learned to make this fact an asset in the sense that I was flexible enough to take on any kind of job. I was willing to learn new skills as well as use what I already knew to keep the group on a reasonable pace.

3.7 RECOMMENDATIONS

If I could start this project over, I think I would have been more assertive in trying to get roles. I think, at the beginning of this project, I was afraid of coming off as too aggressive to the rest of the group that I allowed myself to get any task that still needed to be done. Because of this, I feel like I was viewed as a weak link for a good portion of the project. I wish that I had been more upfront with the rest of my group and not been afraid of coming across negatively. I think, if I did that, I could have proven myself more and gotten some more useful experience out of the experience.

If we had more time to work on the project, I would have liked to further enhance the physical design of the project perhaps by replacing the visible water bottles we used for the water loop and the humidifier with more subtle containers, such as with smaller bottles completely enclosed in another structure so they cannot be seen. I think this would have given the project a more natural look and could have looked both more interesting and more accurate to how water flows in the generation of geothermal energy. I would have also liked to incorporate more information in the game about how geothermal energy is used in different regions of the country, and to what extent. However, I feel like appropriately incorporating this aspect into our quiz would have required a lot more time—between research, designing questions, and redesigning the GUI and code—than we could have been able to put in on top of building, writing the reports, and our other classwork. I think that what our final product does and shows is great, but, with more time, we could have added in so many more details and features.

JOHN CHIARAMONTE

4.1 INTRODUCTION

PROBLEM STATEMENT

Fossil Fuels make up about 80% of energy generation in the United States [25], and people are not mobilizing fast enough to stop greenhouse gas emissions and transition towards renewable energy. Geothermal energy is a sustainable solution to use as an alternative energy source because it satisfies the triple bottom line of sustainability. After implementation, it does not cost much to maintain compared to other forms of energy generation. It does not produce any harmful emissions and completely recycles all materials used in the energy generation process [26]. Finally, geothermal power plants do not take up a ton of space, leaving room for areas to be developed around a power plant, even in a densely populated metropolitan area like Boston. People typically do not know what geothermal energy is, how it works, or why it would benefit them and the planet in the long term, so we will design a museum exhibit that teaches kids about geothermal energy in a fun and engaging way, accessible to kids of all learning styles. Our design will be engaging and eye-catching, with an interactive GUI component that will keep kids engaged with the material. The exhibit will also display a working, moving model of a geothermal power plant. The exhibit will need to be able to be carried by one person comfortably and not have any sharp edges or other characteristics that would prevent anyone from interacting with it in accordance with Universal Design Principles.

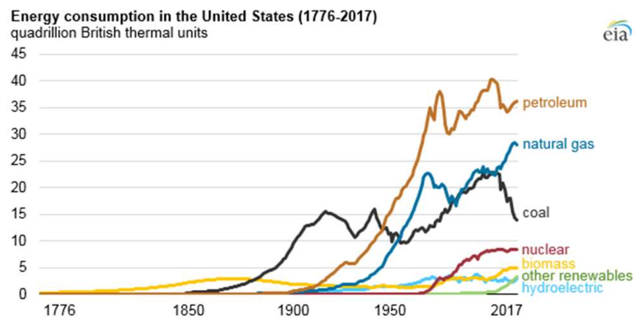

Fig. 29. A graph depicting energy generation from different sources in the United States. Fossil Fuels contribute about 80% of electricity [25].

INTENDED BENEFICIARIES

With our design, we hope to educate the thinkers of the next generation on the importance of sustainable energy generation through the lens of geothermal energy. If successful, kids will understand the importance of renewable energy generation and eventually become educated citizens who can use their voice to influence the direction of the nation, pushing companies and lawmakers to transition to 100% renewable energy. Everyone on the planet benefits from cleaner air and cheaper energy, and if we don't make the transition soon, "climate change is expected to cause growing losses to American infrastructure and property and impede the rate of economic growth over this century" [27].

SUSTAINABILITY IN ENGINEERING

Engineers design the world around us, from cars, busses, and trains, to our cellphones and laptops, and even the plants that power it all. Engineers have a responsibility to create designs that emphasize and take into consideration three things: culture, the environment, and profit. More and more designs in today's capitalist marketplace focus solely on profit and seek to shape culture around them, rather than benefit society and adapt to changing cultures. For example, products like the iPhone are (allegedly) designed with planned obsolescence in mind [28]. While this practice generates massive profit for the company, it warps culture, creating a cult around the company that further bolsters their sense of self-importance and pads their bank accounts. The design isn't sustainable with respect to profit because it is, by nature, cost prohibitive and only purchasable by the upper middle class and above, and is still replaced every year by an ever price-increasing model. The product isn't sensitive to people because it requires extremely cheap, sometimes exploitative labor in foreign countries to produce, and plants produce harmful emissions that further damage the environment and people's health [29].

The iPhone is a perfect example of a product that is wildly successful but horribly unsustainable. The values of the demographic that they produce to are warped by the all-encompassing culture that they create. The people that buy Apple products value high society and status, but the wider market values low prices and products that last, which is why the vast majority of the smartphone market share is Android Phones [30].

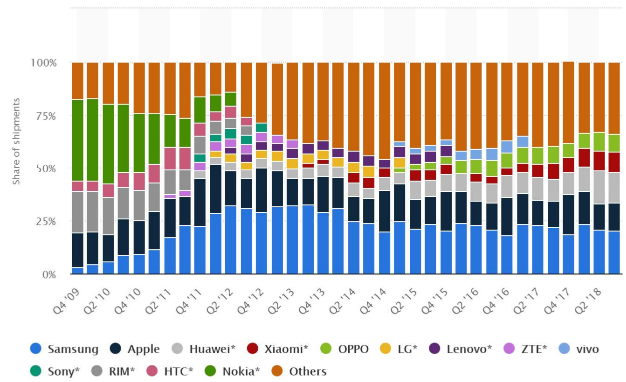

Fig. 30. A bar graph of worldwide smartphone market share by company. Apple remains stagnant as new players grow their market share [30].

For a product or engineering solution to be truly sustainable, it needs to benefit everyone without excluding the poor and vulnerable in our society. Things like clean energy, including geothermal energy, are sustainable designs because they consider everyone in society. Geothermal energy is clean, producing little waste in most styles of power plants, and in power plants that do produce waste, the byproducts can be sold back into the market for use in new products [26]. It doesn't take up a lot of space on the surface, so geothermal plants can be installed in crowded areas, which doesn't impede on overpopulated cities, which appeals to the rapidly urbanizing culture, and, after a steep initial investment, geothermal energy plants don't cost as much to maintain as other styles of power plants [31].

PROJECT OBJECTIVES

The objectives for the project are relatively simple: we want to create a museum exhibit that teaches the client about how geothermal energy works and why they should be in favor of using it. The exhibit will feature a functional model of a geothermal power plant as well as some sort of interactive component in the form of a GUI and tactile input.

The functions of this exhibit are both extensive and difficult to execute upon. There is a fully functional, flow-rate adjustable, leak-free water circulation system to display the moving water in a geothermal power plant. The exhibit also has a 12V RGB LED strip and 5 other individually addressable indicator LEDs for various components on the model. There is a working, rate adjustable motor running to demonstrate the motion of a turbine and a generator. The GUI and backend is all programmed in MATLAB, and is interfaced with through two push buttons and one 4-way joystick as seen in Fig. 31.

Fig. 31. The User Control Panel on the front of the exhibit. Pictured is two buttons and a joystick so the users can buzz in and then use the joystick to make their selection.

Due to the nature of the project, there are a ton of constraints on what we are and are not able to do, both because of assigned constraints and then the constraints of our group. We had to fund the entire project for under $100, which, after purchasing wood, a pump, a humidifier, and a joystick, proved to be very difficult as seen in Appendix J. The size of the exhibit was initially gigantic in our first cardboard prototype, which we saw as a major flaw because it would not be easily carried by one person when built out of wood. We had to shrink it down dramatically to make it feasible for one person to carry as well as be much more aesthetically pleasing for users. A major goal was to make the exhibit accessible for all, so we were limited in design decisions by the universal design standards, which we upheld to the best of our ability. Perhaps the biggest constraint presented to us was time. Each

Milestone asked more and more of the group with seemingly less and less time, and getting the project done within the hustle and bustle of the semester was an extreme challenge, but we prevailed nonetheless.

4.2 BACKGROUND

RESEARCH

Geothermal Energy is used not just for power generation, but also solely for changing the temperature of water for applications such as heating and cooling homes.

For electricity generation, I mainly looked at the model of a dry steam power plant, as seen in my market research image, referenced later in Fig. 33. As shown by the figure, a dry steam power plant works by using the earth's heat to create steam which turns turbines and generates electricity.

In the case of heating and cooling homes, geothermal energy can be used to heat homes in the winter and cool them in the summer, as seen in products such as the Bosch Geothermal heat pump. Since below about 6 feet, the ground maintains a relatively constant year-round temperature, this property can be manipulated throughout the year to get water to a certain constant temperature to be used throughout the house to heat in the winter and cool in the summer [32].

ETHICS

As engineering students, we have a moral responsibility to pass on our knowledge in a truthful and accurate way. The third fundamental canon of the National Society of Professional Engineers says that engineers "issue public statements only in an objective and truthful manner" [33]. If that phrase is extrapolated, it can be interpreted that engineers have a fundamental responsibility to not withhold information, and therefore educate the next generation with all the knowledge that we were given. Our exhibit attempts to educate the next generation on the importance of geothermal energy in hopes that they can become informed citizens and the world can transition towards clean energy.

Part of the sixth fundamental principles of the National Society of Professional Engineers is to "enhance the honor, reputation, and usefulness of the profession" [33]. The goal of this principle is ensuring the future of the engineering profession, and part of this oath is to ensure that the future is populated by educated engineers. Our exhibit can inspire the next generation of engineers to design geothermal energy plants and focus the next generation of thinkers on the importance of clean and sustainable energy generation.

UNIVERSAL DESIGN

Universal design is "The design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design" [34]. There are specific guidelines set by organizations such as the Boston Museum of Science and the Center for Universal Design.

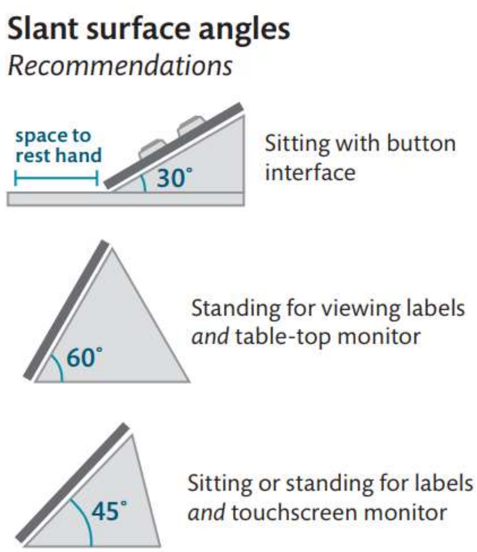

Fig. 32. Boston Museum of Science recommendations for angles of tabletop components [35].

The premise for Universal Design is to ensure that everyone no matter their physical, cognitive, or social ability can interact and get a full experience out of any design [35]. It is important because, particularly in a museum setting, everyone deserves an equal opportunity for a positive learning experience no matter their level of cognition or physical ability.

For our project we used the guidelines set out by the Boston Museum of Science [35]. For the screen in our exhibit, we used about a 60° angle, which is the recommended angle for a table-top non-touchscreen monitor as seen in Fig. 32. The buttons are placed on a 45° angle, which is slightly steeper than the recommended 30° angle, but that recommendation is only for when people are interacting with the exhibit while sitting down. Users will be using our exhibit when standing up, and we believe that the slight increase in angle was a valid tradeoff to ensure fluidity within our design and ensure a small, sleek footprint given the rear protrusion of our buttons and joystick and our unwillingness to build an unwieldy platform to prop up the exhibit.

4.3 METHODOLOGY & ORGANIZATION

The organization of our project revolved around the guidelines that we outlined as a team in our team contract (See Appendix A). In drafting the contract, we wanted to ensure equitable and high-quality work from all members with less emphasis on the project manager than perhaps some other groups have expressed. All our major design decisions were made as a group with at least a majority if not unanimously, as many were.

For each assigned Milestone, we had an hour-long meeting discussing our goals, how and when we were going to achieve them, and all guidelines laid out in the rubric. It was in this meeting that the initial Gantt Chart was created and everything was scheduled for the week. This meeting proved invaluable to us as a team because without it, we would have been stepping over each other while simultaneously not knowing what to do: utter chaos. We assigned each person specific tasks and deadlines, and it is thanks to this intense scheduling that our strategic procrastination ended up succeeding.

I was the project manager during Milestone 4, which was the most difficult Milestone up to that point. We had to transition from cardboard to an entire project built with final, wooden materials. It was a massive undertaking and we were extremely crunched for time. As project manager, the first thing that I did was create a tentative schedule for every item that needed to be done on specific days. This included things like meetings, build days, programming, CAD modeling, etc. I itemized and distributed tasks to the people on my team whom I knew were best at them. At the initial Milestone meeting, we made the Gantt Chart based on my initial schedule and further refined which tasks were distributed to whom. Each person had certain deliverables for every day of the week that I wanted to see, and almost everything was done on time. During build days, because I am stronger in wiring and coding, I took initiative and delegated different roles to build the physical prototype while I worked on my part of the Milestone, wiring and programming. As they were building, I received periodic reports and offered feedback, but made sure to never micromanage what my team was doing. I believe we worked efficiently, respectfully, and effectively, and the results exceeded our expectations. Under my leadership, we experienced the largest leap in progress throughout the entire project, and I could not be prouder of my team for making it happen.

4.4 ALTERNATIVES, EVALUATION AND EVOLUTION

Before we decided on Geothermal Energy, we had a meeting where we discussed possible topics for the Milestone 1 assignment. My contribution to this meeting involved the development of the "revolutionary" product: Wastebasketball. Wastebasketball was an arcade basketball style game where users shoot in different hoops representing different methods of waste disposal. I thought it was amazing, but my team overruled in accordance with our team contract and we all agreed on geothermal energy as our project topic. We performed a Duncker Diagram Problem

Analysis to further explore what was the main problem concerning geothermal energy. We concluded that not enough people, namely children, know about geothermal energy, so we wanted to educate them.

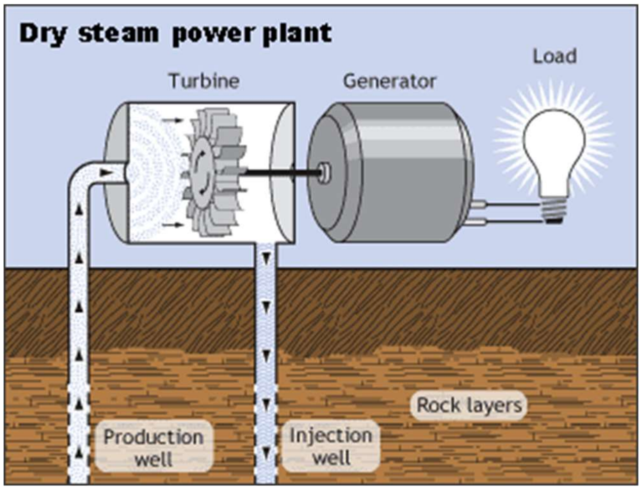

Fig. 33. My market research image of a dry steam power plant. A dry steam power plant generates electricity directly from steam that turns a turbine and turns a generator [36].

In Milestone 2, each member in our team produced research, market research images, and concept drawings based on what they wanted our exhibit to look like. My market image, pictured above in Fig. 33, portrays a dry steam power plant, one of the simplest forms of geothermal power plants to understand. I picked this image because it was simple to break down and understand, and I thought that kids would be able to understand an exhibit based on that diagram. We also produced our first concept drawings in this Milestone. In my drawing, pictured in Fig. 34 to the right, I designed an exhibit where a model of a dry steam geothermal power plant is juxtaposed with a laptop screen displaying a map. In the exhibit, users would tap on states on the map and the exhibit would react based on how geothermal energy is used in that state. My teammates liked that idea a lot and based on our Kepner-Tregoe decision matrix (See Appendix B), we decided to make my exhibit design the base for our group's project. While meeting with our mentor, TA Chan, and showing him these concept drawings, he told us that my design, and the designs of all of my teammates, were much too large. My initial dimensions were 3'x3'x4', which, at the time, didn't seem absolutely absurd as was suggested (See Fig. 34 below). In the AutoCAD model for this Milestone, we shrank the dimensions down to 2'x2'x2'-6". While this was still much too big, we were on the right track.

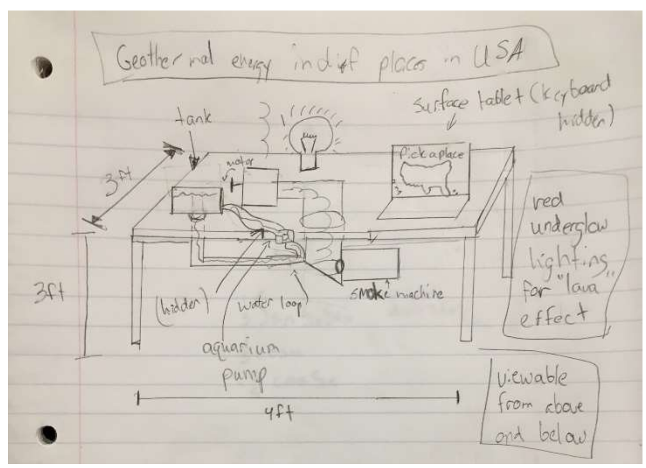

Fig. 34. My concept drawing for a project based on how geothermal energy is used in different parts of the country. The dimensions are far too big, so we changed it for the next Milestone, but kept the base design moving forwards.

For the third Milestone, we created our first cardboard model based on our design drawing from Milestone 2. This drawing had a giant hood on the top of the exhibit, blocking view from the sides, so we decided, as a group, to cut them off for increased visibility; however, we still wanted to keep the bottom enclosed to demonstrate the underground component of a geothermal energy power plant. We didn't change anything else about the exhibit, and constructed our cardboard prototype based on the original dimensions laid out in Milestone 2. After building and seeing our dimensions fully realized, we finally understood just how monstrous it was and sought to shrink it for the next Milestone. One great piece of feedback that we received in the Milestone 3 town hall was the limited visibility in the bottom compartment from an angle due to the vertical wall. We then, as a group, discussed possible solutions and decided to implement a slant into the next design, which became the basis for our final model as seen in Appendix C.

In Milestone 4, we looked more at our feedback from the Milestone 3 town hall meeting and decided to change gears with the concept of our interactive component in the exhibit. Instead of a map that users tap on to explore regions in the United States, we wanted to use buttons and joysticks to give tactile input and better engage the user with the external components of the exhibit, rather than focusing on touching the touch screen. We also heard in the Milestone 3 town hall meeting that our design was still massive, so we made a drastic change in size, as seen in Appendix C. We decided that a good use of our buttons and joystick would be a competitive quiz game, so after we built the entire exhibit out of wood, we went and created a basic proof-of-concept quiz to demonstrate the functionality in our buttons and joystick, as well as the RGB LED strip, which appeared for the first time in this Milestone.

4.5 FINAL DESIGN

DESCRIPTION

Our project, "Geothermal Energy: A Super Power Source," is an Incredibles-themed two-person competitive quiz game where the user's goal is to answer questions correctly in order to defeat each other while powering the IncrediDrill and defeating the Underminer. The final design can be seen in Fig. 35 on the next page.

Fig. 35. The final design of the museum exhibit as displayed in the Museum of Science. It features a working model of a dry steam geothermal power plant and a functional GUI controlled by buttons and a joystick, all wrapped up in an Incredibles theme.

The project can be broken down into two main parts: the functional model of a geothermal power plant, and the interactive quiz game with joystick and button inputs.

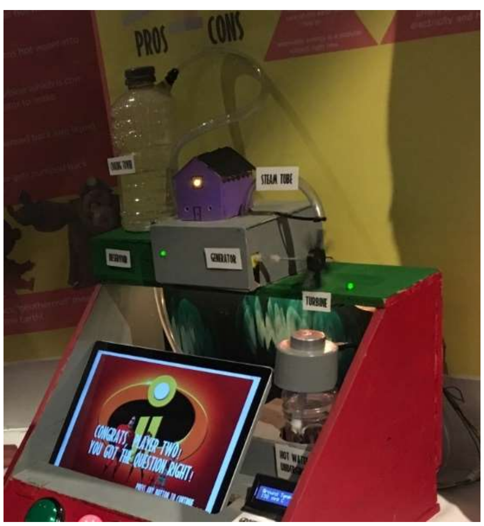

Fig. 36. A close-up of the geothermal power plant model. Each individual part is labeled so that users can make the critical connections necessary to answer the questions in the quiz game.

The model of a geothermal power plant consists of, functionally, a working self-cycling water loop with pump, a humidifier to demonstrate steam produced, a motor with attached turbine to demonstrate electricity generated, and lights near each part to indicate to the user what is being referenced in the game's different questions, as seen in Fig. 36 to the left.

Additionally, there is an LCD near the humidifier to tell the user the "ground temperature" and better illustrate the different uses for geothermal energy throughout the country. An RGB LED strip is placed inside the exhibit to both draw users in with pretty lights and illustrate the underground part of a geothermal power plant with colors like red and orange to emphasize the heat of the earth.

The interactive quiz game is displayed on my Surfacebook 2™ and features a MATLAB pseudo-GUI with image files being cycled based on the players' position in the game using the *imshow* function. Users interface with the GUI through the two buttons and one joystick tilted 45° on the front of the exhibit. With each question, users first buzz in to answer, then the one who buzzes in first answers, and then, if correct, the user gets a point and the "power bar" fills up incrementally, illustrating the ultimate goal of working together to defeat the Underminer. If the user gets a question wrong, it is added to a list of incorrect questions to be recycled at the end, ensuring that the users see and answer correctly every question in the game before finishing, ensuring maximum learning potential. After the last question is answered correctly, the users are prompted with the final score and then a message indicating that they collectively defeated the Underminer and learned about geothermal energy while doing so.

A typical run through the game would go as follows: two users approach the exhibit because the flashing lights, spinning motor, and steam draw their attention; they use the buttons to advance past the instructions to the first question of the game; with each question, the exhibit turns on and off different components of the power plant model to make sure the users look at and understand them in order to answer the questions; the users buzz in using the buttons and the first one to buzz in gets to answer the displayed question; if right, the user gets a point and the power bar fills, but if wrong, information on why it was wrong appears on the screen; after all 7 questions are answered, the game cycles through the wrong questions until every question has been answered correctly; after this, the game displays the final results and a message explaining that the two users finished the game and defeated the Underminer while learning about geothermal energy. After the end of the game, the program loops back around and restarts, waiting for the next two users to approach.

BETA TESTING RESULTS

During beta testing, we designed a short survey that each testing participant took at the end of their experience, as seen in Appendix E.

Our first question revolved around what the user thought that the exhibit was trying to teach them. Will's 11-year old brother hit the nail on the head when he mentioned that the exhibit was trying to teach him how geothermal energy worked and how it is used in different parts of the country. Because he is part of our main demographic, this was a great sign that we were achieving our learning goals.

The second question asked how fun the exhibit was. We received an average of 9 out of 10, which was pleasantly surprising since we had been scrutinizing over how to make the exhibit more fun, and completely changed our design after being told by our mentor that it was boring.

The third and fourth question asked for the users favorite and least favorite parts of the exhibit. We received the best feedback from these questions and have made adjustments in accordance with this feedback. Will's little brother and mother noted that the text in some of the questions was hard to read, so we adjusted it to make it better color coordinated against the dark background. Funnily enough, Will's mom thought the turbine was cheesy, which was her son's 3D printed component, so we all laughed at him.

CONTRIBUTIONS

My main contributions to the project, other than taking up managerial responsibilities throughout the course of the project, involved the coding and wiring of the exhibit. Every piece of wiring was put into place by me, and I wrote every line of code by myself. I was also the main person involved with designing and building the functioning water loop, which was its own day of work for me entirely, as shown by the initial test pictured below in Fig. 37.

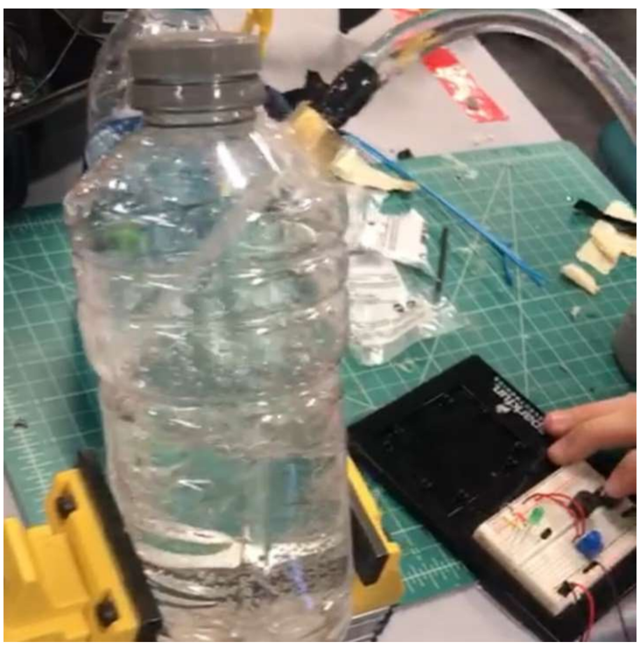

Fig. 37. The first test of the functioning closed-loop water circulation system. To test, I build a simple standalone circuit and performed a leak test for over an hour.

Appendix G shows the wiring diagram that I created, which took on about 10 iterations and modifications before the final product. One of the major hurdles was designing circuits for the RGB LED Strip and the humidifier, motor, and pump. The RGB LED strip and pump both run on 12V power, so I had to learn how to use MOSFET transistors to provide isolated voltage to only those two components. The motor and humidifier also were not provided with enough current from the Arduino's digital output pins, so I again used MOSFETS, this time using the Arduino's 5V rail, which provided enough current to power both devices simultaneously.

A major problem we had while preparing for Milestone 5 was that all of the electronics just stopped working at the same time and the Arduino mega board was not able to receive any uploads from either MATLAB or the Arduino IDE. We thought that we were going to have to buy another board or rework the entire project to run on two boards, but luckily, after tearing out every piece of electronics and rewiring them, the board functioned as expected and the exhibit, and my life, seemingly, was saved. The rats' nest of wires can be seen in Fig. 38.

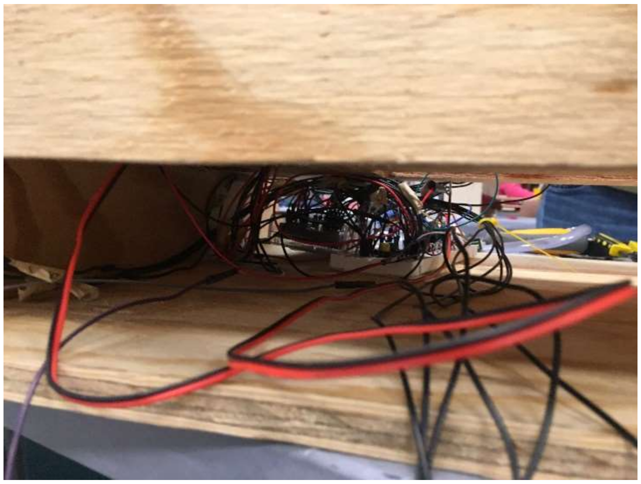

Fig. 38. The rats' nest of cables that power the exhibit. If we were to do it again, we would change our strategy and make an open bottom for easy access so we don't have the same problems with lose wires that we experienced during development.

Appendix F shows all the code used in the project, which I programmed myself. I took notes on how my group members wanted everything to work, and then I sat in a corner for a few hours, iterating over the work from the previous Milestone every week. The program itself is not extremely complicated in nature, and once I got the scaffolding functions completed (question_plot, setRGB, pump, button_input, etc.), programming the main game file was not too difficult because it required only references to work that I had already done.

In the eleventh hour, I also provided my graphical design skills and designed and formatted the poster with the content written by my teammates. I was able to put the entire poster together in under two hours, printing minutes before the library plotter printers were set to close on the night before exhibition day.

While it may seem on the surface that I took an undue burden upon myself, I assure you that I was more efficient at these tasks than my group members would have been, and in discussion, we all agreed that the work done was fair and equitable.

Resources

Our group just barely managed to meet our budget of $100, spending exactly the right amount of money. Our main large expenses were the wood, joystick, pump, poster, and humidifier, which together account for over half of our budget (See Appendix J).

Because I am the only one with Amazon Prime in the group, I took care of anything that needed to be ordered online. This included the pump, tubing, power supply screw terminals, joystick, humidifier, and MOSFETs. I also already owned the Arduino Mega, case, and large breadboard, so I was able to get my parents to ship it to me for no cost, so we could use them in our project. We plan on splitting the cost after the fact based on which parts of the exhibit people would like to remove and keep for their own personal projects.

I have spent more time on this project than anything else I have ever done apart from my iPhone app. Over the course of the semester, I have spent over 100 hours tirelessly toiling away at each and every part of this project. See Appendix K for a detailed breakdown of my week-to-week duties and work hours.

4.6 CONCLUSION

OBSERVATIONS FROM EXHIBITION DAY

Walking into the Boston Museum of Science on exhibition day was a completely surreal experience. I had to take a step back and admire the fact that I had the opportunity to present my group's own original work in a place which has cemented itself as one of the greatest science museums in the world. After jolting back into reality, we set the exhibit up and, after repairing the 12V supplemental power connector, we were able to observe how our actual target demographic would interact with our exhibit.

For the most part, the kids who interacted with the exhibit understood it better than the adults, who thought too much and didn't read any of the directions or supplemental materials. The best group of kids was two (about) ten-year-old boys who jumped right into the competition and used the exhibit as intended, as seen in Fig. 39. It truly excited me to see them compete to buzz in first and then watch them as they critically thought out their answers using the tools that we gave them, pointing out the different parts of the exhibit that were moving. In particular, they answered question 3 about re-condensation correctly because they saw the water turn on and talked about the steam must go back through a tube to turn into water again. The kid in the Naruto costume then proceeded to thank me and do a Fortnite dance as he walked away, so I'm pretty sure we did our job.

Fig. 39. The two ten-year-olds who showed both the most excitement and the best understanding of the exhibit of the entire day.

Overall, I would say that our exhibit was successful and adhered to every point we originally laid out for it in our problem statement. We strove to create an exhibit that would effectively teach children about geothermal energy, and based on how kids interacted with our exhibit, I would say that we achieved our goal; however, as Greg from the Museum of Science told me, in his opinion, the most important part of a successful museum exhibit isn't retention of concrete factual information, but the critical thinking skills that the user exhibits to properly interact with the exhibit. He commended us for having multiple methods for the users to find and create complex connections to successfully find information for themselves and interact with the game, and hearing validation from an engineer who creates exhibits for a living truly validated my already proud feeling towards the performance of our exhibit.

REFLECTIONS ON LEARNING

This project has taught me more about working with electronics than anything I've ever done. It wasn't the assigned work that made me learn, but the limits of our team's imagination. My learning in this project isn't limited to just wiring; however, I also learned a lot about woodworking, fabrication, and iterative design.

For instance, a lot of our design revolves around cleverly hiding wires in and around walls, which required a ton of holes to be drilled all around the exhibit. When needing a large hole, I initially used a gigantic drill bit without a pilot hole. This resulted in the drill not even scratching the wood let alone drilling through it. Stepping up from tiny drill bits incrementally to large ones yielded much cleaner results in the long run, a technique I hadn't heard of before.

With regards to circuitry, I taught myself how to use the most important invention of mankind's history: the transistor. We needed to use 12V power for both the pump and the RGB LED Strip, but the Arduino Mega can only supply 5V by itself, so I did research and found out how to use a transistor. After initially spending an hour with the transistor included in the Sparkfun kit before realizing that it was a temperature sensor and they didn't include transistors in the kit anymore, I ordered MOSFET transistors that I saw used in a YouTube video [37] and taught myself how to use them for the RGB LED Strip. I then used this knowledge and applied it to the pump, humidifier, and motor to get the higher voltage and higher amperage components working off of the digital output pins on the Arduino Mega.

Fig. 40. Our cardboard model from Milestone 3. This iteration was extremely large and unwieldy, and the enclosed nature of the underground left it difficult to see the screen from an angle.

Milestone 3 in particular taught me a lot about the importance of modeling and iterative design. I thought that my initial design was very clever because it looked very clean on paper. It was sleek and modern and illustrated everything we wanted, but when it was modeled out of cardboard, it was easy to see that the proposed specifications were gigantic and unwieldy. The enclosed nature of the prototype made it nearly impossible to see the inner components from any angle aside from the front (as shown in Fig. 40). Feedback taken from that Milestone, probably the best feedback we have received through this entire process, helped us change the design immensely, both physically and with respect to the game design, which our mentor, TA Chan, found boring.

Reflections on Working in a Team

Despite my extensive reservations about working in a team coming into this semester, I believe that it has been an overall positive experience, and I think my teammates will agree that we worked together very well and treated one another professionally, responsibly, and fairly.

Many challenges presented themselves to me throughout the semester, largely from the fact that I had limited experience working in a team for such an intense project with such short timing between deadlines. Coordinating meeting times in between the day-to-day responsibilities of four individuals was very difficult, but all my teammates were very flexible.

One lesson that I had to learn was that not everyone thinks the same way that I do, and that fact presents both positive and negative attributes. I needed to create much better documentation for wiring and programming than I am used to in order for my teammates to understand the work I was doing. I had to learn how to better communicate my ideas with other people and handle negative feedback in a constructive manner. When we created initial project proposals, I thought that my idea, Wastebasketball was far superior than geothermal energy, but the group reached a majority consensus and I had to accept that. That decision has turned out much better in the long run, as I now know that Professor Schulte Grahame had to prevent about four other groups from doing similar projects.

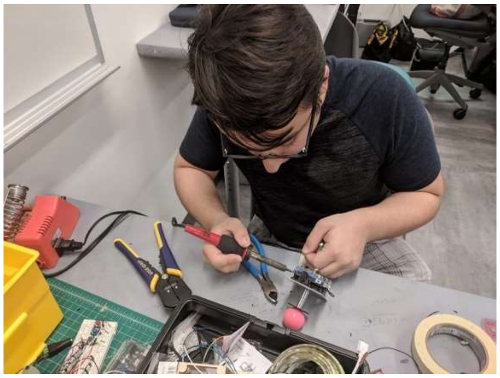

Fig. 41. Me sitting in my corner in the First Year Engineering Learning and Innovation Center, unbothered, as I solder the leads onto the joystick for use in Milestone 4.

My ability to be managed is very good; however, I do not work well with micro-management or people watching closely over my shoulder as I work. I think that I have a very valuable set of skills and I know what I can and cannot execute on. I do not appreciate someone telling me each and every thing I need to be doing. With my wiring and coding work, I did my best work when I got instructions from my groupmates on what they wanted, sat in a corner in the FYELIC, and soldered/wired/coded/built for hours straight with no interruptions, as seen in Fig. 41 above. I made every deadline and met or exceeded expectations with the quality of my work because the project managers and other groupmates respected my personal space.

I was the project manager for Milestone 4, which was, in my opinion, the most difficult Milestone up until that point. Before we started working on it, I created a timeline of events similar to what our Gantt chart would become, but I created deliverables for each and every person on each meeting day, and, apart from one component in the report, everything was executed by me and my teammates on time according to the schedule. I believe that it is important to give people concrete deliverables so that they know what is expected of them in a specified timeframe.

One of the things that we are most proud of as a group is pulling off an exhibit with actual flowing water. The haters said it could not be done, but nevertheless, we persisted. We only had one leak, and it was due to a faulty pipe connection that was fixed within 3 minutes. We retested the water loop multiple times without any further leaks and proved that water-based projects can be done with actual water if the group is dedicated enough.

The biggest asset to our team dynamic was our clear communication. We were very effective in getting things done because each of us was extremely direct in what we expected from each other in terms of quality of work and what needed to be done. Our common sense of humor made it very easy to communicate and destress during stressful times, and our constant joking led to a jovial atmosphere conducive to collaboration.

4.7 RECOMMENDATIONS

If I were to make recommendations for the next group of students who do this project, I would say this: keep it simple—not in the sense that the design has to be "easy," but from what I have seen with our own exhibit and exhibits of our peers is that the more engaging projects execute one concept very seamlessly rather than 15 concepts mediocrely. Our exhibit, in some respects, tries to do too much. It uses the most complicated electrical system out of the rest of the projects, but it is not totally necessary to do so. The difficulty does not in itself make our exhibit any more or less successful than any other, but it does make the exhibit much more difficult to build and troubleshoot. I would also recommend seriously planning out space where the wires will be run and the internal components stored, because, while we accounted for space in the underside of our exhibit for wiring, we attached a bottom panel that only allows for about three inches of clearance to reach hands in and edit any circuitry, which caused a lot of headaches.

There is no major substantive change that I would make to the exhibit; however, we had one problem with the humidifier that we never found a perfect solution for. If a tube is directly attached to the spout of the humidifier, it creates a very cool smoky effect which can be diverted in any direction; however, because of the nature of the cool mist and tubing, we had many issues with the mist condensing in the tube and water flowing back into the humidifier, preventing it from functioning properly. We discussed various methods for a drainage spout design but did not have enough time to design and implement it into our exhibit. A properly routed mist tube would have better illustrated our point and would have looked very cool.

Overall, I am proud of our exhibit and my performance in this class, and I have no regrets on how I've spent time working on this exhibit.

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AUTHOR BIOGRAPHIES

John A. Chiaramonte was born in Queens, New York, in 2000. He graduated from Regis High School in Manhattan in 2018 and is currently on track to graduate from Northeastern University with a Bachelor of Science (BSCompE) in Computer Engineering and Computer Science in 2023

From 2016-2018, he worked on an independent iOS development project called CoinTrak, an app that tracked movements in the cryptocurrency market, which led him to further explore Computer Engineering and Computer Science. He has experience programming in over 5 languages and works with Arduino, Raspberry Pi, and holds interest in developing for Windows, Mac, and Linux. He was also the captain of the Regis High School CyberPatriot team, which earned the first-place title in the Air Force Association's CyberPatriot X Competition.

Mr. Chiaramonte is a member of the Northeastern University Robotics Club as a member of the Swerve Electronics Project. He is also involved with Northeastern's ski club, the Downhillers, and will be a mentor for Stacked Cornerstone in the Spring 2019 semester.

Joseph M. Durkin was born in Boston, Massachusetts, in 2000. He graduated from Central Catholic High School in Lawrence, Massachusetts in 2018 and is currently a freshman at Northeastern University in Boston. He currently studies electrical and computer engineering, with plans to receive both a B.S. and an M.S. along with two minors in mathematics and economics.

From 2014 to 2018, he remained highly active in his high school's community, joining many student organizations and holding some important leadership positions, including National Honor Society Treasurer, Campus Ministry Peer Leader and Retreat Leader, and Catwalk4Cancer model, giving him a wide range of experiences that have prepared him to act in and lead many different situations. His interest in engineering came from his experience in high-level math and science classes, specifically his junior AP Physics teacher who would discuss his past experiences in engineering projects with great passion.

Mr. Durkin is currently a member of the Northeastern University chapter of IEEE. He also plans on getting involved with the Survivor: Northeastern organization and hopes to work in the FYELIC in the spring 2019 semester.

Noah O. Foley was born in Boston, Massachusetts on September 2nd, 1999. He received his high school diploma from Foxborough High School, Foxborough, Massachusetts, in 2018, having achieved college credit in this time from Rhode Island College, and is currently pursuing a combined B.S. degree in chemical engineering and biochemistry from Northeastern University, Boston, as of 2018.

From 2014-2018, he was Foxborough High School Class Secretary and French National Honor Society Secretary. While in these positions, he organized/developed multiple high school events, including a Prom and World Language and Culture Day, equipping him with problem-solving/design skills that he is now utilizing in the engineering field. In 2018, he worked in the fast food industry and volunteered at a community farm-stand, intriguing him in the chemical processes humans use to create edible food and food products. He is currently pursuing a research assistant position with Pinto Laboratories to manipulate microbial communities to protect/improve public and environmental health and the functional reliability of drinking water and wastewater systems.

Mr. Foley was a recipient of the Bausch + Lomb Honorary Science Award and is a member of the NASA Mars Greenhouse Team of the Students for the Exploration and Development of Space, the Northeastern Debate Team, and the Times New Roman Satire Magazine.

Will Hodge was born in Marlborough, Massachusetts in 2000. He graduated from the Advanced Math and Science Academy Charter School in Marlborough in 2018, and is currently pursuing a bachelor's Degree in Mechanical Engineering from Northeastern University.

He became interested in engineering through his science and math courses in high school, including AP Chemistry, AP Computer Science, and AP Calculus. He has also always enjoyed building things and figuring out how things work, which is why he likes mechanical engineering. In high school, he was Vice Captain of the Quiz Bowl A Team that competed at Nationals and on WGBH's High School Quiz Show. He was a first violinist in the Claflin Hill Youth Symphony Orchestra, and an employee at Kumon and Apex Entertainment Center. He also volunteered as a mentor for Science for Shooting Stars, an organization that taught daycare children about science.

Mr. Hodge is a member of the American Society of Mechanical Engineering. He will also be a mentor for stacked Cornerstone next semester. Additionally, he will be a mentor at the FYELIC in the Spring 2019 semester.

APPENDICES

APPENDIX A – TEAM CONTRACT

CONTACT INFORMATION

Name	Email	Phone Number
John Chiaramonte	chiaramonte.j@husky.neu.edu	(917)-846-3124
Joe Durkin	durkin.j@husky.neu.edu	(617)-634-9735
Noah Foley	foley.no@husky.neu.edu	(774)-300-7493
Will Hodge	hodge.w@husky.neu.edu	(508)-624-0161

RESPECT

A group member may be five minutes late once (excluding family and medical emergencies) to a team meeting or when submitting work past the agreed upon deadline without penalty. Out of courtesy for his fellow group members, a late member must always notify all other group members via the WhatsApp chat or other equally effective means; it is also requested that if someone can predict their lateness, they should proactively send a message so that the group knows in advance. After this first infraction, the team member at fault must purchase Dunkin' Donuts for every member of the group, up to $5 per person. If a member is over one hour late to submission or is late to a second meeting, they must take the group members out to Five Guys that same business week. Further infractions will yield more Five Guys penalties unless the group unanimously decides to increase punishment.

All group members will make their best effort to allow other members to speak to completion before speaking themselves (i.e., no interruptions). The project manager reserves the right to re-center the room (silence the group and begin a new point) if conversation starts to go off track and members begin to interrupt each other, even if this occurs unintentionally. Likewise, the three other group members are allowed to unanimously reassert to the project manager that the latter should avoid interrupting and focus on productive group conversation as well in the case that they lose track of themselves. If two or three group members disagree on any significant issue or decision, the other member(s) will mediate to a point at which all four agree. In the case that no resolution can be met even with mediation, a third party (Professor Schulte and/or Chan in the case of a group conflict and the OSCCR in the case of a more personal issue) will be contacted to officiate an arbitration process. In the unlikely scenario that all four members cannot agree on a solution, Professor Schulte, Chan, another TA, or a member of the First Year Engineering Lab will be contacted.

COMMITMENT

Our prime directive for quality will be for each member to compare their work to the rubric three times and then ask another team member to peer-review it with the rubric before submission. They will have completed the work ahead of time, allowing one hour for these potential final edits, then another hour for the peer to check over the work before submission. This quality will be therefore valued by the rubric's point breakdown, with every member striving for the maximum amount of points. For work that does not have rubric parameters assigned to it, all four team members must be satisfied with the quality a day before it is actually due, allowing this time for additional edits to ease any party's concerns. At this time, members must unanimously decide what changes and additions are required so that all members are in agreement and one person is not overloaded with unnecessary/unreasonable work edits. This quality will thus be valued by the group's overall satisfaction with their work (as the group will inherently have the best possible quality work when it has reached a point that no one has qualms, and everyone believes the work reflects their fullest efforts to do well) and peer evaluation/constructive criticism sessions every two weeks.

If someone violates the above commitment policies, notably by submitting low quality work for two or more consecutive assignments, that person will be subject to the same punishments as outlined in the "Respect" section (i.e. the first offense will require the purchase of Dunkin' Donuts and subsequent offenses will require the purchase of Five Guys for the team). The person in question will also be more closely monitored by the project manager to ensure they are getting their work done by the proposed times and are putting in a full effort into their portion of the project. This monitoring will decrease over time and cease once the person has proven they can and will diligently keep up with assignments.

Each team member has a copy of the others' class, work, and extracurricular schedules and so will be able to determine when each member is free to work. Team members will not ask others to skip classes, work, or extracurriculars for a group meeting, and the group will not have meetings in which plans and work are discussed without another member because they could not attend. Unless the team cannot complete their work during the week, weekends will be reserved as non-work days. In general, no team member will be expected to attend a group meeting past 12 AM on weekdays, or in between classes with less than a two-hour grace period. However, individual work may be completed at any time night or day as long as it is completed by the due date set by the group or project manager. The group will meet every Wednesday at 5:00 at a predetermined location (either a Snell Library group work room reserved in advance or a study lounge at East Village) for a predetermined amount of time set that morning, depending on the workload that particular week, typically two to three hours. If a second team meeting is required, the team will meet on Thursday evening in a predetermined location for a predetermined amount of time.

TRANSPARENCY

Decisions will be made via an open forum in which all group members present their thoughts and arguments, with all final decisions being decided once a unanimous conclusion is reached. If the vote is split, the decision at hand will be discussed further before a second vote. If the group is deadlocked once again, the conflict will be resolved with the protocols discussed above in paragraph 2 of the section titled "Respect."

Before each meeting, group members will present a brief summary of their work for that week. All relevant documents will be able to be viewed and edited by all members concurrently by the commencement of every weekly meeting, satisfying the time parameters listed in “Commitment,” as this meeting day will most often be one day before the previous week’s deadline to allow for adjustments. For written work, Google Docs and Drive will be used to share all work, and a (private) GitHub repository will be used to store all relevant code and other documents.

INCLUSION

The group has created a WhatsApp group chat which will be its primary mode of communication. WhatsApp has a function where members of a group chat can see who has read each message, so group chat engagement can be directly evaluated. Each member must attempt to view and verbally acknowledge any updates to the conversation regarding scheduling and/or work/strategy every two hours between the hours of 9AM and 11PM. Group members should contribute by writing at least one thoughtful progress update each day to spur information dissemination and possible advice between members. Not every progress update has to contain actual progress as long as progress is being made over the course of the work week. This update is primarily to help reassure the other members that work and time is continually being considered.

FAIRNESS

When we get a list of our assignments for a Milestone or other group project, we will have a meeting where, as a group, we estimate approximately how long each assignment should take. This way, work can be divided equitably so that each group member will have to dedicate equal amounts of time to this project and cannot manipulate estimations to their benefit, as no one knows who will be doing what until after the estimation discussion is completed. This method will be more effective than giving everyone roughly the same number of assignments, as some assignments could take longer than others and will not result in an equal distribution of work. Work will also be divided based on our individual strengths to maximize both efficiency and quality of the final product.

In terms of work distribution, we will attempt to avoid conflict through the method described above. However, if conflict does arise, we will set aside some time during a meeting to look over the division of work and evaluate where there is a point of contention. We will then discuss why the current division is the way it is and propose ideas on how it could possibly be distributed more fairly.

TEAM GOALS

1. We will design a sustainable final project that both educates children in the disciplines of science and/or engineering and presents an innovative idea that can positively impact the world.
2. We will get an A on our final project.
3. We will work together as a cohesive unit, rather than as four individuals, making conscious effort to minimize unconstructive disagreement.

4. We will understand each other's strengths so that we can most efficiently work together and delegate individual tasks.

INDIVIDUAL GOALS

John Chiaramonte

1. I want to become better at programming as part of a team, rather than just individually like I am used to.
2. I want to learn more about electronics and become proficient at working with Arduinos and similar microcontrollers.

Joe Durkin

1. I want to gain experience with CAD and Arduinos so I can become better with programming and design, two areas where I currently lack experience yet have always wanted to develop.
2. I also want to explore different aspects of engineering so I can begin creating a path to follow in the future, giving me a deeper understanding of what I may want to do with the rest of my life.

Noah Foley

1. I want to be able to efficiently navigate and utilize all the Cornerstone affiliated softwares (AutoCAD, MATLAB, etc.), but also gain the ability to learn how to think like an engineer so that I may quickly learn to operate any software like these for my professional work.
2. I want to earn new methods of spurring creativity and innovative thinking, which will be vital to any future design work required of me.

Will Hodge

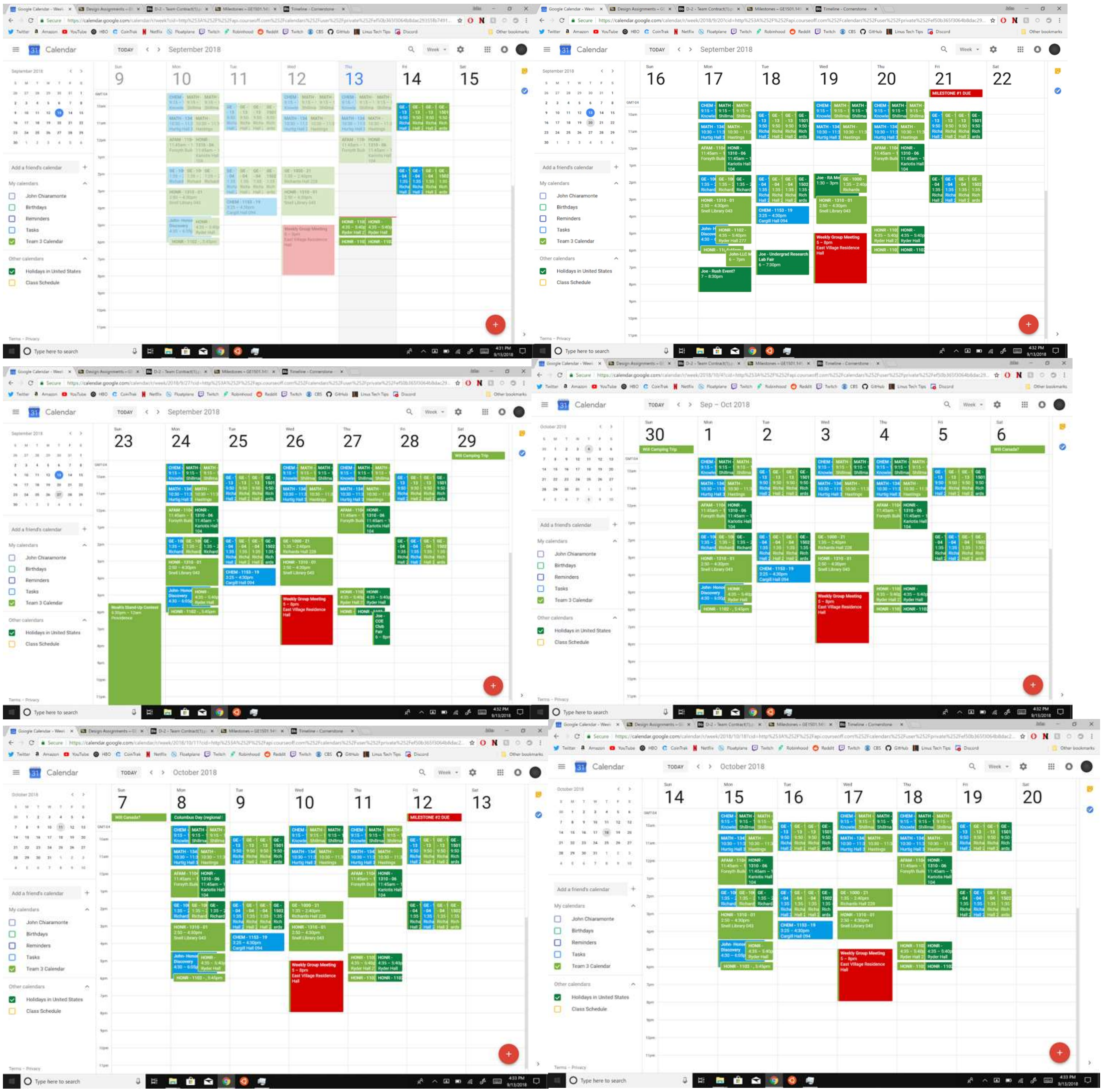
1. I want to become proficient at using CAD, as I have almost no experience with it right now.
2. I want to learn how to code Arduinos and hardware in general.

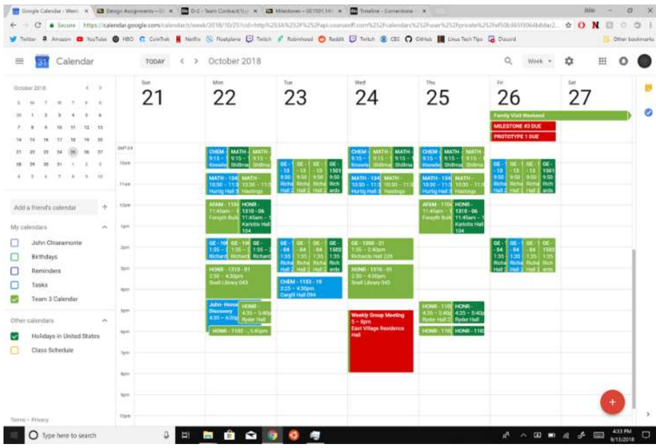
TEAM ROLES (MILESTONES 1-4)

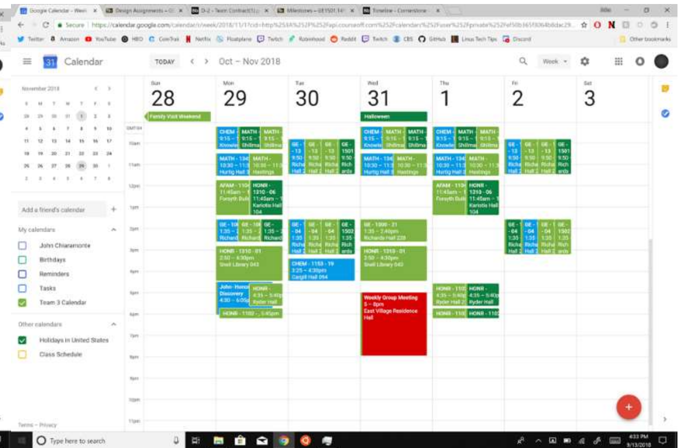
The following order of project managers for the first four Milestones was chosen with a random list generator, as was agreed upon unanimously:

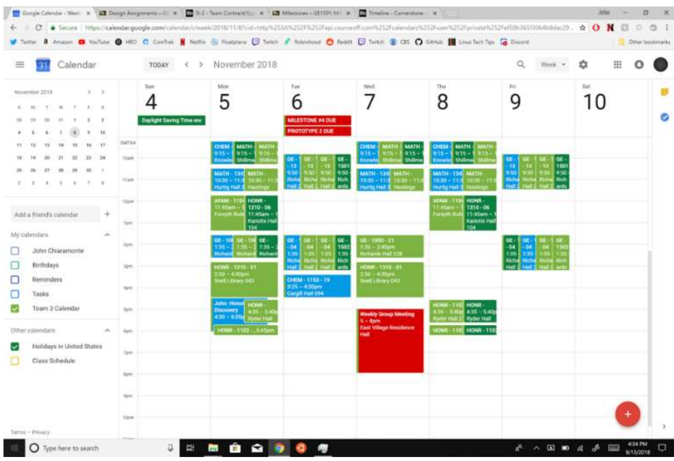
1. Noah Foley
2. Will Hodge
3. Joe Durkin
4. John Chiaramonte

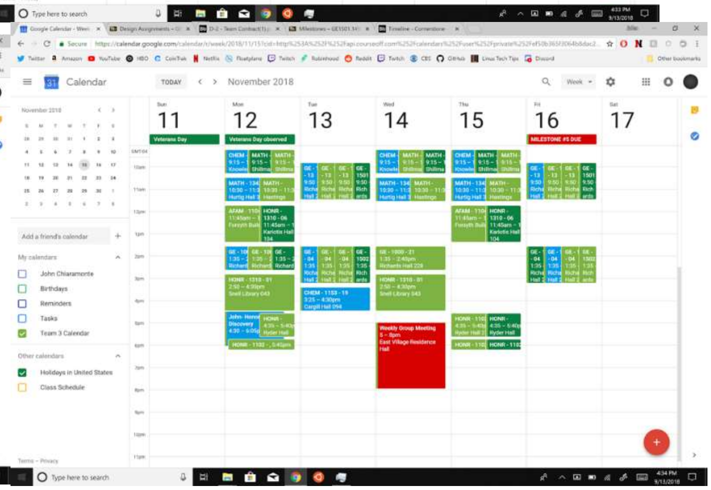
TEAM CALENDAR

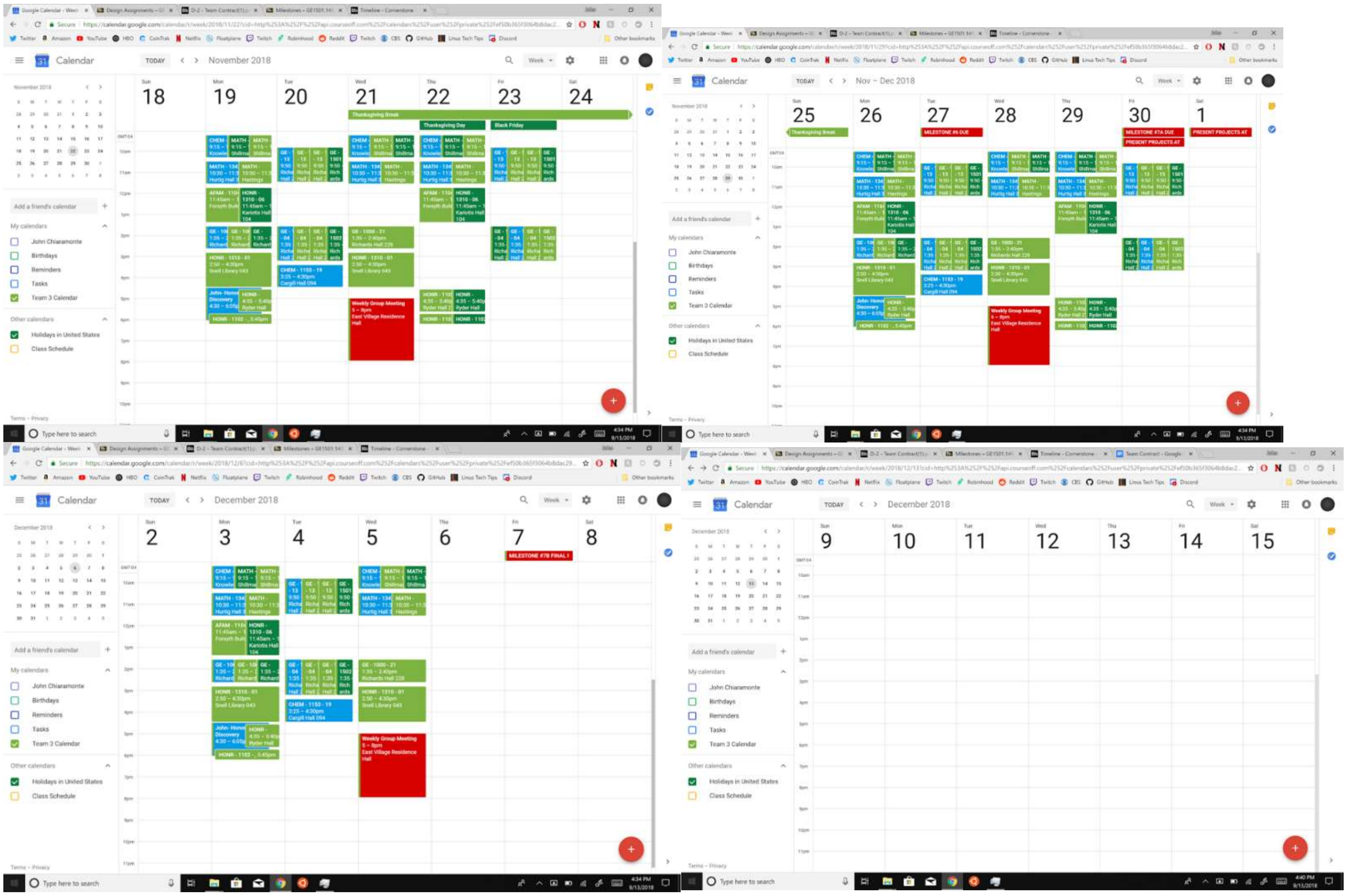



Calendar
October 2018


Calendar
Oct – Nov 2018


Calendar
November 2018


Calendar
November 2018



D-1: Our team calendar complete with our individual schedules

SIGNATURES

John Chiaramonte

John Chiaramonte

Joe Durkin

Noah Foley

Noah Foley

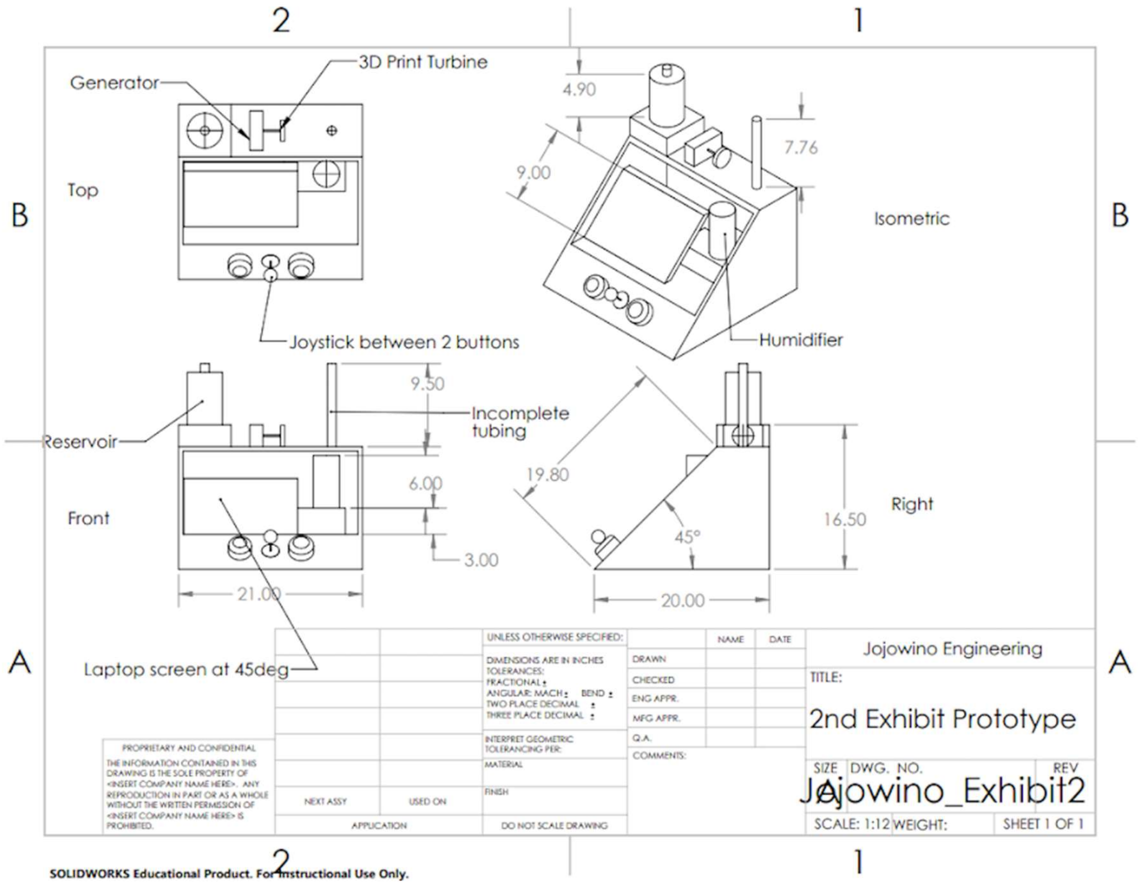
Will Hodge

APPENDIX B - DECISION ANALYSIS

This table is our Kepner-Tregoe decision matrix that we created when deciding whose design to make our final design. The three most important factors to us were the feasibility, cost, and safeness of the design. We determined that Joe's design was not feasible because we did not have the depth of knowledge about geothermal energy that would have been required to execute the project successfully. This eliminated Joe's design from contention. Then, we all agreed upon the six "wants" and their weights, and all came to a consensus about the ratings for each category for the three remaining projects. John's design scored greater than 10% higher than Will and Noah's design, meaning that his was the design we decided to base our final design on.

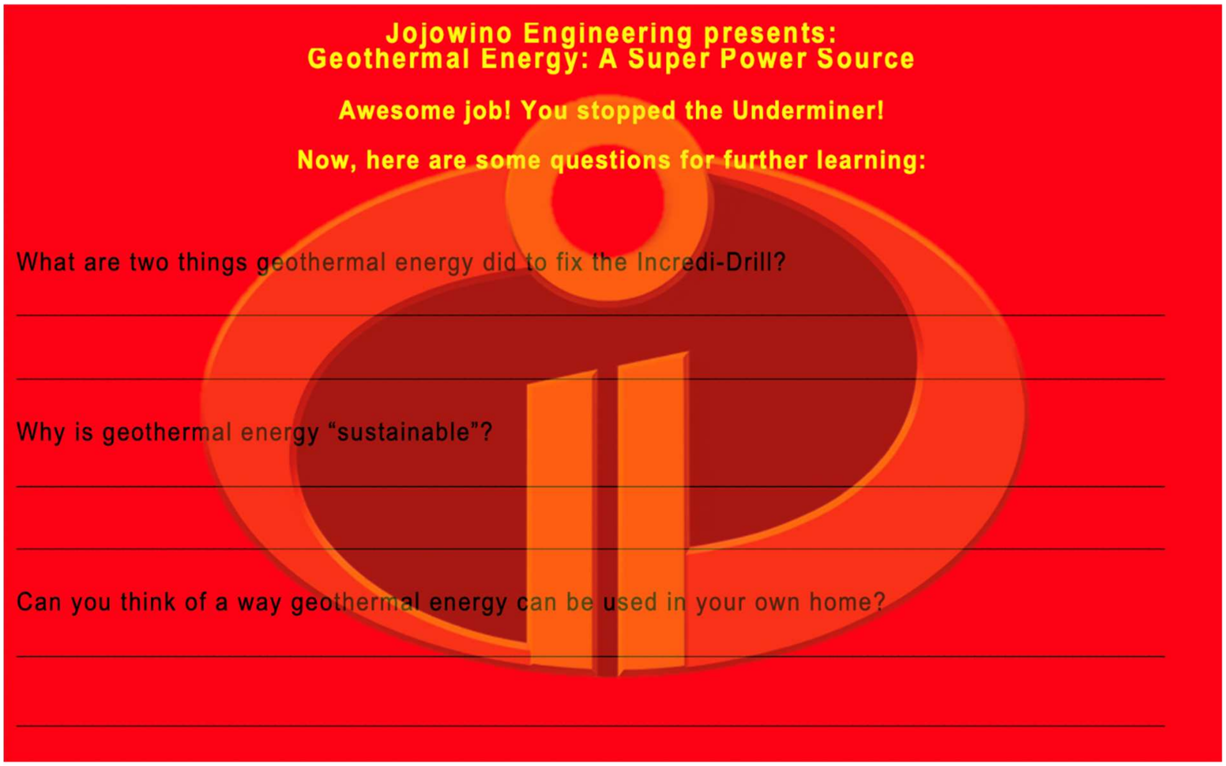
		John's Design		Joe's Design		Will's Design		Noah's Design	
Musts									
Feasible		GO		NO GO		GO		GO	
Budget Friendly		GO		GO		GO		GO	
Safe		GO		GO		GO		GO	
Wants	**Weights (1-9)**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**	**Rating**	**Score**
Easy to Move	6	6	36		0	7	42	8	48
Interactive	7	9	63		0	6	42	5	35
Fun	8	9	72		0	6	48	7	56
Durable	8	5	40		0	7	56	5	40
Educational	9	9	81		0	8	72	7	63
Accessible	7	10	70		0	9	63	8	56
Totals			**362**		**0**		**323**		**298**

D-2: Our Kepner-Tregoe decision matrix when evaluating the original design sketches from Milestone 2



D-3: Our final SolidWorks drawing for our exhibit's design

APPENDIX D – EDUCATIONAL HANDOUT



D-4: The front side of our educational handout

D-5: The back side of our educational handout

APPENDIX E – PRODUCT TESTING RESULTS

For our tester feedback, we asked Will's 11-year-old brother, Will's mother, and Kees, a Northeastern freshman majoring in CS and International Affairs, the following four questions:

1. What do you think this exhibit was trying to teach you?
   A. Kid: Geothermal energy and how it is used in different areas
   B. Mom: Geothermal energy and the process of producing it & how it works
   C. Non-engineer: How geothermal power works
2. Rate how fun this experience was on a scale from 1-10:
   A. Kid: 8
   B. Mom: 10
   C. Non-engineer: 9
3. What was your favorite part of the exhibit?
   A. Kid: The physical model, the Incredibles theme
   B. Mom: How we could program the exhibit to act differently in different scenarios, water looked like it was actually boiling
   C. Non-engineer: The GUI font, the backgrounds
4. What was your least favorite part of the exhibit?
   A. Kid: Text was hard to read in the GUI
   B. Mom: Turbine was "cheesy looking" and doesn't make a statement, strange font
   C. Non-engineer: Looks unfinished

With this feedback, we made some changes to our exhibit. Kees told us that the project looked unfinished, so we painted the rest of it and added a background to tie the aesthetics together. We plan on editing the GUI to make the text more readable, which will be one of the last changes we make. We're happy with the "fun-ness" ratings and the first question, as this was what we were trying to teach users.

M6_GUI.m (Main Program)

```
%M6_GUI.m
%John Chiaramonte 11/18/18


clc;
clear;


%add path for LCD Library
addpath('C:\ProgramData\MATLAB\SupportPackages\R2018a\toolbox\matlab\hardw
are\supportpackages\arduinoio\arduinoioexamples\SDKExampleLCD\');
%build arduino object
a = arduino('COM6','Mega2560',
'libraries','ExampleLCD/LCDAddon','ForceBuild',true);
%create LCD object
lcd =
addon(a,'ExampleLCD/LCDAddon',{'D53','D51','D49','D47','D45','D43'});
initializeLCD(lcd);

%print to LCD
printLCD(lcd,'Welcome to');
printLCD(lcd,'Our Exhibit!');
pause(.2);

%turn pin 13 off for RGB LED strip
writeDigitalPin(a,'D13',0);

%set PWM of pin 2 for LCD contrast
writePWMDutyCycle(a,'D2',.4);

%set figure parameters
s = get(0, 'ScreenSize');
figure('Position', [0 0 s(3) s(4)])
set(gcf,'MenuBar','none');
axes('pos',[0 0 1 1])

%MAIN GAME LOOP
while true
    %welcome screen
    welcome_screen(a);

    %instructions
    tell_instructions();
```

```
    pause(.01);
    while true
        input = button_input(a);
        if input == 5 || input == 6
            break
        end
    end


    current_choice = 1;
    score = [0 0]; %player 1 score stored in index 1, player 2 in 2;


    correct_answers = [4 3 4 2 1];

    wrong_questions = [];
    number_wrong = 0;
    number_right = 0;

    %master loop for questions
    for question_index = 1:5

        reaction_case(a,question_index,lcd);
        pause(.1);

        fprintf('Question %i\n', question_index);

%imshow(imread(strcat('images/questions/question_',num2str(i),'.png')));

        results =
question_plot(a,question_index,correct_answers(question_index),number_righ
t);

        if results(1) == 1 %if first player answered
            if results(2) == 1 %if correct, add 1 point
                score(1) = score(1)+1;
                number_right = number_right + 1;
                imshow(imread('images/player1right.png'));
            else %if incorrect, add 1 point to other player
                %score(2) = score(2)+1;
                number_wrong = number_wrong + 1;
                wrong_questions = [wrong_questions,question_index];

imshow(imread(strcat('images/questions/incorrect/incorrect_',num2str(quest
ion_index),'.png')));
            end
        else %if second player answered
            if results(2) == 1 %if correct, add 1 point
```

```
                score(2) = score(2)+1;
                number_right = number_right + 1;
                imshow(imread('images/player2right.png'));
            else %if incorrect, add 1 point to other player
                %score(1) = score(1)+1;
                number_wrong = number_wrong + 1;
                wrong_questions = [wrong_questions,question_index];

imshow(imread(strcat('images/questions/incorrect/incorrect_',num2str(quest
ion_index),'.png')));
            end
        end

        pause(.01);
        while true
            input = button_input(a);
            if input == 5 || input == 6
                break
            end
        end

        plot_score(score);

        pause(.01);
        while true
            input = button_input(a);
            if input == 5 || input == 6
                break
            end
        end

    end

    disp ''
    disp 'WRONG QUESTION LOOP'
    disp ''


    wrong_size = size(wrong_questions);
    number_wrong = wrong_size(2);
    wrong_questions;
    number_right;


    %secondary loop for incorrect questions
    while number_right < 5

        %instructions
```

```
        imshow(imread('images/tryagain.png'));
        pause(.01);
        while true
            input = button_input(a);
            if input == 5 || input == 6
                break
            end
        end

        %disp '----------------'
        for j = 1:wrong_size(2)

            wrong_questions(j)

            if wrong_questions(j) ~= 0

                pause(.1);
                reaction_case(a,wrong_questions(j),lcd);
                results =
question_plot(a,wrong_questions(j),correct_answers(wrong_questions(j)),num
ber_right);

                if results(1) == 1 %if first player answered
                    if results(2) == 1 %if correct, add 1 point
                        score(1) = score(1)+1;
                        number_right = number_right + 1;
                        wrong_questions(j) = 0;
                        imshow(imread('images/player1right.png'));
                    else %if incorrect, add 1 point to other player
                        %score(2) = score(2)+1;

imshow(imread(strcat('images/questions/incorrect/incorrect_',num2str(wrong
_questions(j)),'.png')));
                    end
                else %if second player answered
                    if results(2) == 1 %if correct, add 1 point
                        score(2) = score(2)+1;
                        number_right = number_right + 1;
                        wrong_questions(j) = 0;
                        imshow(imread('images/player2right.png'));
                    else %if incorrect, add 1 point to other player
                        %score(1) = score(1)+1;

imshow(imread(strcat('images/questions/incorrect/incorrect_',num2str(wrong
_questions(j)),'.png')));
                    end
                end
```

```
                pause(.01);
                while true
                    input = button_input(a);
                    if input == 5 || input == 6
                        break
                    end
                end
                plot_score(score);
                pause(.01);
                while true
                    input = button_input(a);
                    if input == 5 || input == 6
                        break
                    end
                end

            end


        end
    end


    %score evaluations
    if score(1) > score(2) %player 1 win
        imshow(imread('images/player1win.png'));
    elseif score(2) > score(1) %player 2 win
        imshow(imread('images/player2win.png'));
    end

    pause(3);

    imshow(imread('images/endscreen.png'));

    pause(3);

    %reset score
    score = [0 0];
end
```

welcome_screen.m (Welcome Screen)

```
%welcome_screen.m
%John Chiaramonte 11/5/18
```

```
function void = welcome_screen(arduino)
    user_has_pressed = false;

    %display welcome screen in a nice figure
    clf;
    set(gca,'position',[0 0 1 1],'units','normalized');
    welcomescreen = imread('images/welcomescreen1.png');
    imshow(welcomescreen);
    pause(1);

    %humidifier on full and motor on full
    fog(arduino,100);
    spin_motor(arduino,100);
    spin_pump(arduino,100);

    writeDigitalPin(arduino,'d23',1);

    %does a rainbow wave with RGB LED strip while constantly checking for
    %input
    while not(user_has_pressed)
        for i = 1:50
            setRGB(arduino,(50-i)*2,i*2,0);
            user_input = button_input(arduino);
            if user_input == 5 || user_input == 6
                user_has_pressed = true;
                break;
            end
            %pause(pause_time);
        end
        if user_has_pressed
            break;
        end
        for j = 1:50
            setRGB(arduino,0,(50-j)*2,j*2);
            user_input = button_input(arduino);
            if user_input == 5  || user_input == 6
                user_has_pressed = true;
                break;
            end
            %pause(pause_time);
        end
        if user_has_pressed
            break;
        end
        for k = 1:50
            setRGB(arduino,k*2,0,(50-k)*2);
            user_input = button_input(arduino);
            if user_input == 5  || user_input == 6
```

```
                user_has_pressed = true;
                break;
            end
            %pause(pause_time);
        end
    end
end
```

tell_instructions.m (Instruction Screen)

```
%tell_instructions.m
%John Chiaramonte 11/5/18

function void = tell_instructions()
    %display the instruction image
    instruction_image = imread('images/directions.png');
    imshow(instruction_image);
end
```

spin_pump.m (Makes pump work)

```
%spin_motor.m
%John Chiaramonte 11/3/18

function void = spin_pump(arduino,intensity)
    %set motor pin to PWM value
    if intensity > 1
        writeDigitalPin(arduino,'d31',1);
    else
        writeDigitalPin(arduino,'d31',0);
    end
    pump_pin = 'D7';
    writePWMDutyCycle(arduino,pump_pin,intensity/100);
end
```

spin_motor.m (Makes motor work)

```
%spin_motor.m
%John Chiaramonte 11/3/18

function void = spin_motor(arduino,intensity)
    %set motor pin to PWM value
    motor_pin = 'D5';
    writePWMDutyCycle(arduino,motor_pin,intensity/100);

    writeDigitalPin(arduino,'d25',1);
```

```
    writeDigitalPin(arduino,'d29',1);

    if intensity == 0
        writeDigitalPin(arduino,'d25',0);
        writeDigitalPin(arduino,'d29',0);
    end

end
```

setRGB.m (Set RGB value for LED Strip)

```
%setRGB.m
%John Chiaramonte 11/3/18

function setRGB(arduino,red_intensity,green_intensity,blue_intensity)

    %pins for red green and blue led strip pins
    red_pin = 'D13';
    green_pin = 'D12';
    blue_pin = 'D11';

    %write to each of them the passed PWM value / 100
    writePWMDutyCycle(arduino,red_pin,red_intensity/100);
    writePWMDutyCycle(arduino,green_pin,green_intensity/100);
    writePWMDutyCycle(arduino,blue_pin,blue_intensity/100);

end
```

question_plot.m (Displays question and returns results)

```
%question_plot.m
%John Chiaramonte 11/4/18

function results =
question_plot(arduino,question_index,correct_index,number_right)

    clf;

    %make file name
    file_name =
strcat('images/questions/question_',num2str(question_index),'.png');

    %plot the initial question.
    set(gca,'position',[0 0 1 1],'units','normalized')
    question = imread(file_name);
    imshow(question)
    power_bar(number_right);
    pause(.1);
```

```
hold on
plot([],[]);

%player buzzing in sequence
while true
    %high refresh rate
    %pause(.01);
    input = button_input(arduino);
    %check for input and break if user presses a button
    if input == 5
        player_buzzed = 1;
        break;
    elseif input == 6
        player_buzzed = 2;
        break;
    end
end

%set image file name for notification
if player_buzzed == 1
    buzz_notification = imread('images/playeronebuzz.png');
else
    buzz_notification = imread('images/playertwobuzz.png');
end

%show the buzz notification image
imshow(buzz_notification);
pause(1);


selected_answer = 1;
user_has_selected = false;

%set(gca,'position',[0 0 1 1],'units','normalized')
%question = imread(file_name);
imshow(question)
hold on
plot([],[]);
%title('Answer the Question!');
pause(.4);

%x from 921 to 3000
%921,3000
%921,921
%3000,3000

%y coords
%580 854
```

```
%971,1267
%1351,1655
%1750,2042

while true
    %clf;
    set(gca,'position',[0 0 1 1],'units','normalized')
    question = imread(file_name);
    imshow(question)
    power_bar(number_right);
    hold on
    plot([],[]);

    %pause(1);

    %title('Answer the Question!');

    if selected_answer == 1
        %horizontal lines
        plot([921,3000],[580,580],'r-','LineWidth',3);
        plot([921,3000],[854,854],'r-','LineWidth',3);

        %vertical lines
        plot([921,921],[580,854],'r-','LineWidth',3);
        plot([3000,3000],[580,854],'r-','LineWidth',3);
    elseif selected_answer == 2

        %horizontal lines
        plot([921,3000],[971,971],'r-','LineWidth',3);
        plot([921,3000],[1267,1267],'r-','LineWidth',3);

        %vertical lines
        plot([921,921],[971,1267],'r-','LineWidth',3);
        plot([3000,3000],[971,1267],'r-','LineWidth',3);

    elseif selected_answer == 3

        %horizontal lines
        plot([921,3000],[1351,1351],'r-','LineWidth',3);
        plot([921,3000],[1655,1655],'r-','LineWidth',3);

        %vertical lines
        plot([921,921],[1351,1655],'r-','LineWidth',3);
        plot([3000,3000],[1351,1655],'r-','LineWidth',3);

    else

        %horizontal lines
```

```
        plot([921,3000],[1750,1750],'r-','LineWidth',3);
        plot([921,3000],[2042,2042],'r-','LineWidth',3);

        %vertical lines
        plot([921,921],[1750,2042],'r-','LineWidth',3);
        plot([3000,3000],[1750,2042],'r-','LineWidth',3);

    end

    %input loop checks for all types of valid input
    while true
        pause(.01); %sets the refresh rate

        input = button_input(arduino);

        if input == 3 %up
            selected_answer = selected_answer+1;
            if selected_answer > 4
                selected_answer = 4;
            end
            pause(.01);
            break;
        elseif input == 4 %down
            selected_answer = selected_answer - 1;
            if selected_answer < 1
                selected_answer = 1;
            end
            pause(.01);
            break;
        elseif input == 5 && player_buzzed == 1%select p1
            user_has_selected = true;
            disp 'PLAYER 1 HAS SELECTED'
            break;
        elseif input == 6 && player_buzzed == 2%select p2
            user_has_selected = true;
            disp 'PLAYER 2 HAS SELECTED'
            break;
        else
            %break;
        end %end input if

    end %end input while true

    if user_has_selected
        break
    end% end user selection break if

end %end while true
```

```
    answer = selected_answer;

    %check if correct
    if answer == correct_index
        is_correct = true;
    else
        is_correct = false;
    end

    results = [player_buzzed,is_correct];
end
```

plot_score.m (plots the scoreboard)

```
%plot_score.m
%John Chiaramonte 11/5/18

function void = plot_score(score)

    filename = 'images/scoreboard.png';
    %set the image
    scoreboard_pic = imread(filename);
    imshow(scoreboard_pic);
    hold on
    %plot the scores at the specified coordinates of the picture

text(434.8,1460.7,num2str(score(1)),'FontSize',150,'HorizontalAlignment','
center','VerticalAlignment','middle');

text(2674,1460.7,num2str(score(2)),'FontSize',150,'HorizontalAlignment','c
enter','VerticalAlignment','middle');
    hold off
    %pause(3); %pause for 3 seconds

end
```

fog.m (Make Fog Machine Work)

```
%fog.m
%John Chiaramonte 11/3/18

function void = fog(arduino, intensity)
    %sets fog machine PWM intensity
    humidifier_pin = 'D6';
    writePWMDutyCycle(arduino,humidifier_pin,intensity/100);
```

```
end
```

button_input.m (gets input from buttons and joystick)

```
%button_input.m
%John Chiaramonte 11/3/18

function input_value = button_input(arduino)

    input_value = 0;

    %digital input pins
    left_pin = 'D24';
    right_pin = 'D26';
    up_pin = 'D28';
    down_pin = 'D30';
    select_pin_p1 = 'D36';
    select_pin_p2 = 'D38';

    if ~readDigitalPin(arduino,left_pin) %left
        input_value = 1;
    elseif ~readDigitalPin(arduino,right_pin) %right
        input_value = 2;
    elseif ~readDigitalPin(arduino,up_pin) %up
        input_value = 3;
    elseif ~readDigitalPin(arduino,down_pin) %down
        input_value = 4;
    elseif ~readDigitalPin(arduino,select_pin_p1) %select player 1
        input_value = 5;
    elseif ~readDigitalPin(arduino,select_pin_p2) %select player 1
        input_value = 6;
    end

end
```

power_bar.m (plots power bar on screen)

```
%power_bar.m
%John Chiaramonte 11/19/18

function void = power_bar(number_right)
    hold on
    middle = 476.0250;
    plot([middle,middle],[1892,1892-number_right*((1892-
695.75)/5)],'r','LineWidth',105);
    hold off
end
```

reaction_case.m (makes exhibit react for passed question)

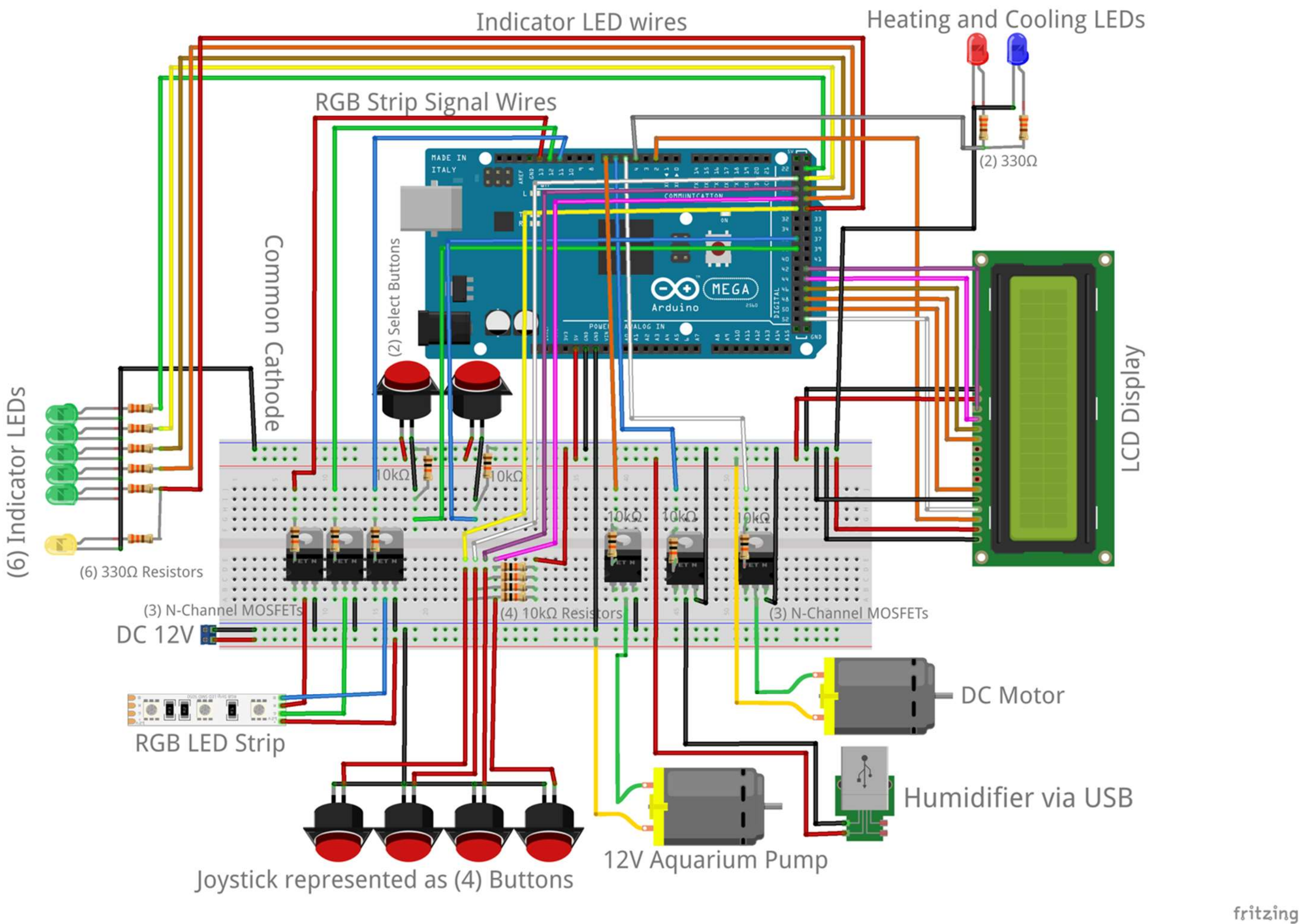
```
%reaction_case.m
%John Chiaramonte 11/18/18
%makes museum exhibit produce a specified set of actions depending on what
%question the user is on

function void = reaction_case(a,question_index,lcd)
    switch question_index
        case 1
            setRGB(a,100,20,0);
            fog(a,100);
            spin_motor(a,100);
            spin_pump(a,0);
            clearLCD(lcd);
            initializeLCD(lcd);
            printLCD(lcd,'Ground Temp:');
            printLCD(lcd,'150 deg C');
            writeDigitalPin(a,'d23',1)
            writeDigitalPin(a,'d4',0)
        case 2
            setRGB(a,100,0,0);
            fog(a,100);
            spin_motor(a,100);
            spin_pump(a,0);
            clearLCD(lcd);
            initializeLCD(lcd);
            writeDigitalPin(a,'d23',0)
            writeDigitalPin(a,'d4',0)
        case 3
            setRGB(a,50,50,50);
            fog(a,100);
            spin_motor(a,0);
            spin_pump(a,100);
            clearLCD(lcd);
            initializeLCD(lcd);
            writeDigitalPin(a,'d23',0)
            writeDigitalPin(a,'d4',0)
        case 4
            setRGB(a,0,0,100);
            fog(a,0);
            spin_motor(a,0);
            spin_pump(a,100);
            clearLCD(lcd);
            initializeLCD(lcd);
            printLCD(lcd,'Ground Temp:');
            printLCD(lcd,'50 deg C');
            writeDigitalPin(a,'d23',1)
```

```
            writeDigitalPin(a,'d4',1)
        case 5
            setRGB(a,100,100,100);
            fog(a,0);
            spin_motor(a,0);
            spin_pump(a,0);
            clearLCD(lcd);
            initializeLCD(lcd);
            printLCD(lcd,'Ground Temp:');
            printLCD(lcd,'250 deg C');
            writeDigitalPin(a,'d23',1)
            writeDigitalPin(a,'d4',0)
        otherwise %turn everything off
            %first set of questions have all high speed
            setRGB(a,0,0,0);
            fog(a,0);
            spin_motor(a,0);
            spin_pump(a,0);
            clearLCD(lcd);
            writeDigitalPin(a,'d23',0)
            writeDigitalPin(a,'d4',0)
    end

end
```

APPENDIX G – WIRE DIAGRAM

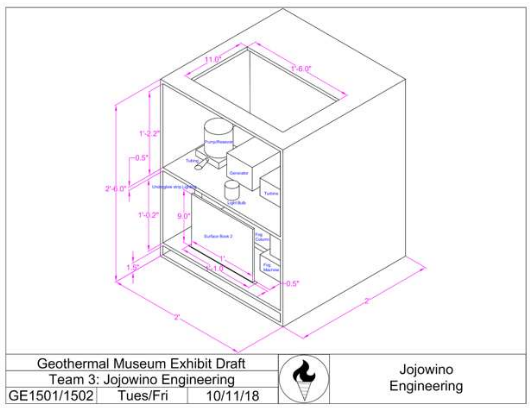


D-6: Our final wire diagram for the electronics in the exhibit

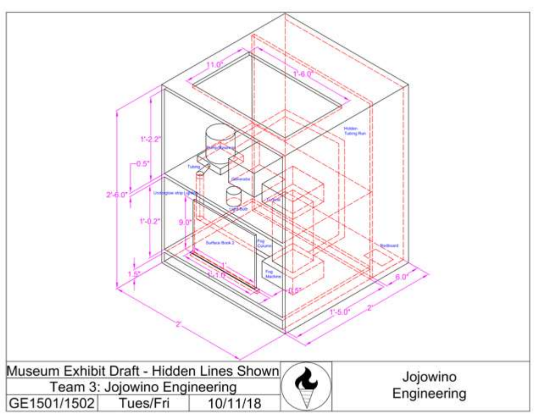
APPENDIX H – PHOTO LOG

EVOLUTION OF THE PROJECT

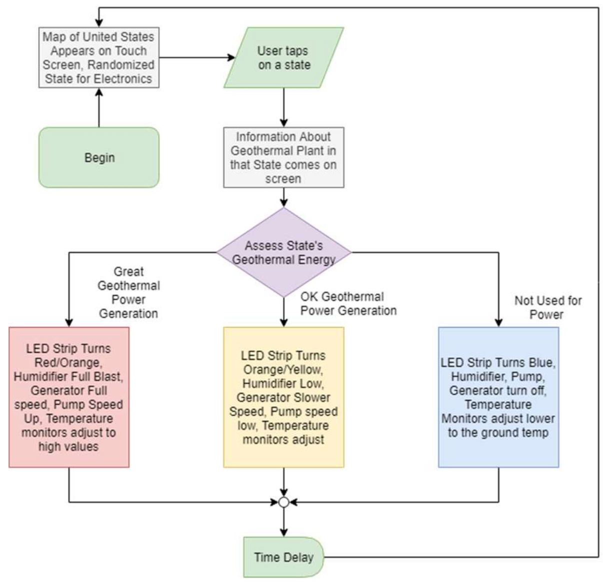
D-7: Our first brainstorming session, where our exhibit was just one concept out of many



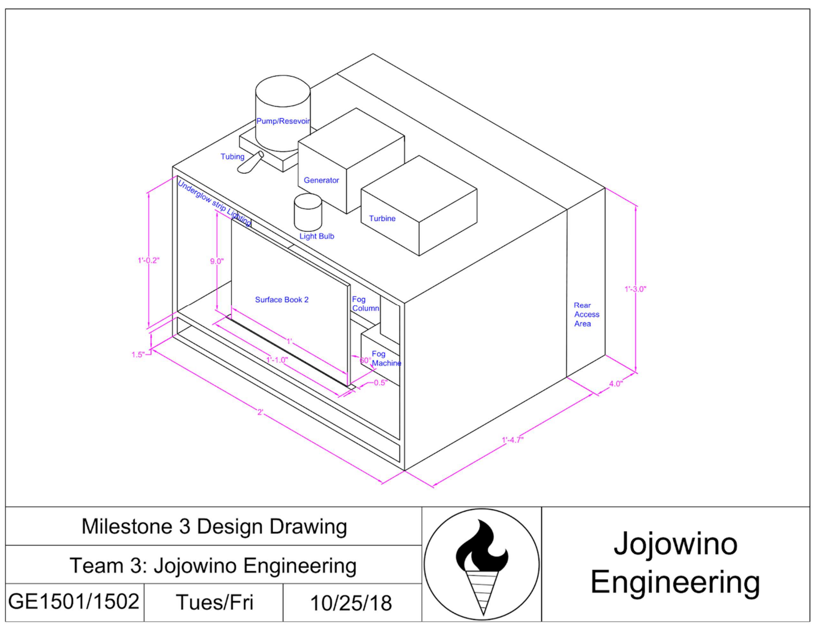
D-8: Our AutoCAD drawing of our original design



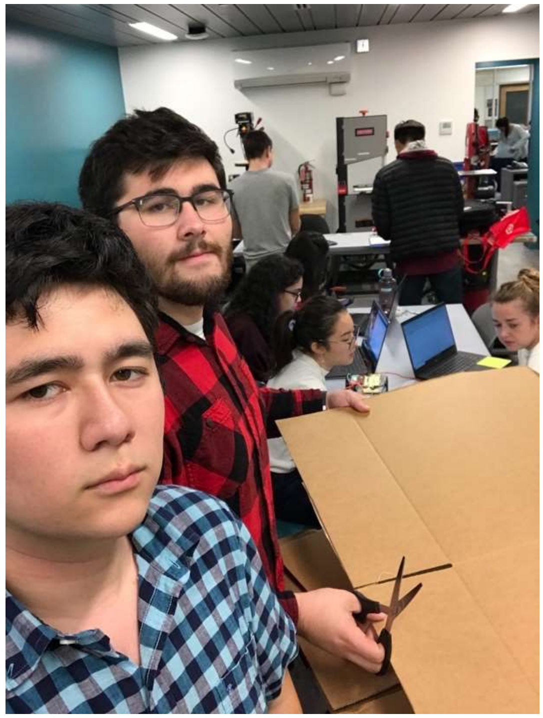
D-9: Our first AutoCAD drawing complete with hidden lines to show the inside components



D-10: Our first flowchart to explain how the electronics will function



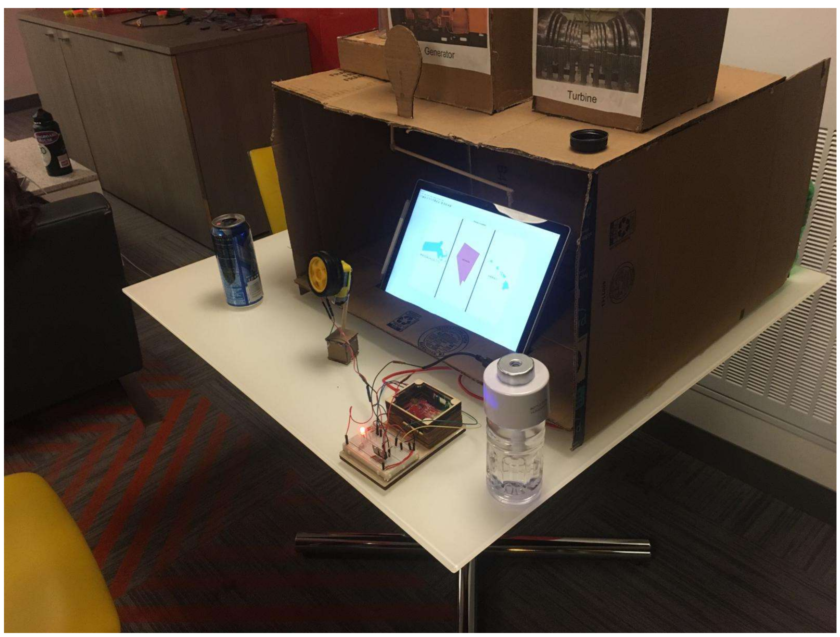
D-11: An updated AutoCAD drawing showing how we changed the prototype from the original design



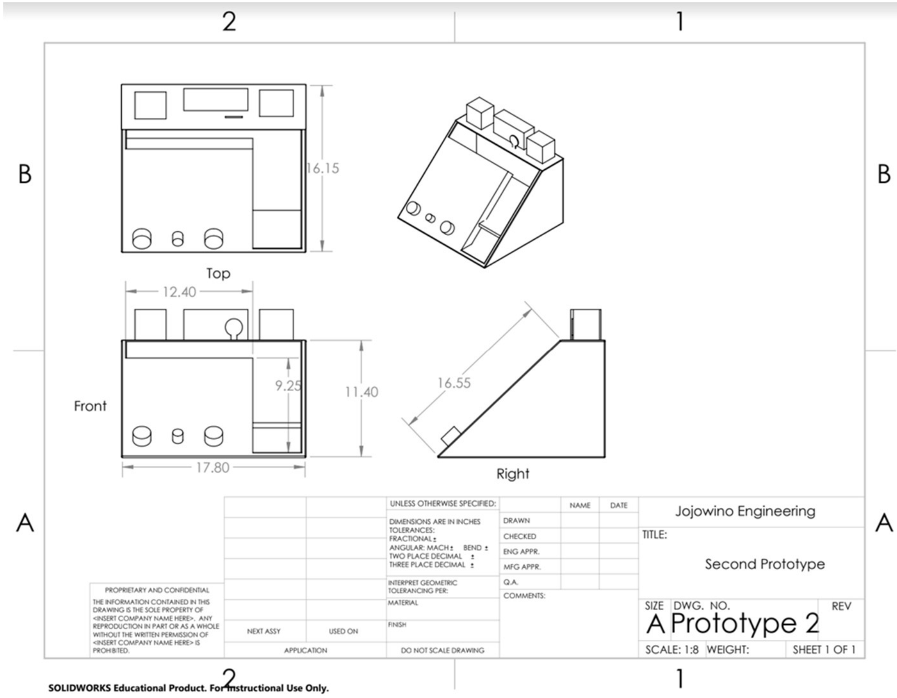
D-12: Joe and Noah in FYELIC beginning to construct the cardboard prototype

D-13: John beginning to wire up the exhibit for Milestone 3

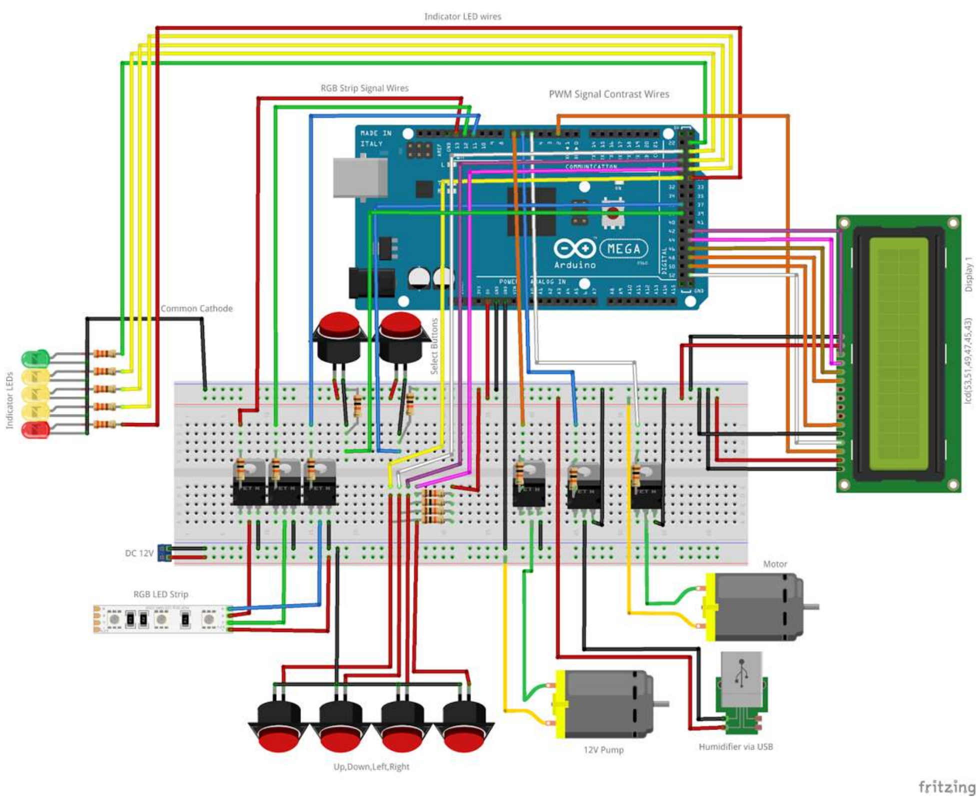
D-14: Will adding some final touches to the prototype



D-15: The completed cardboard prototype, along with the first signs of electronic functionality

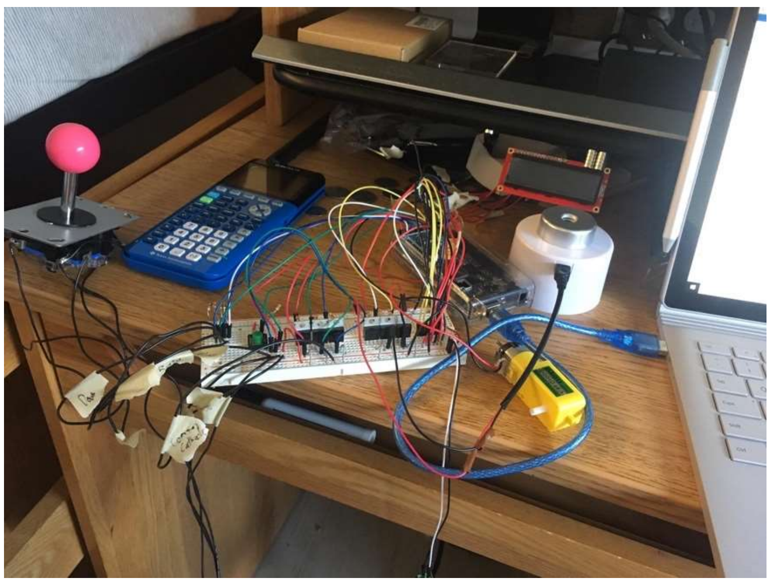


D-16: Our updated design sketch for Milestone 4 based on the Milestone 3 feedback, now made in SolidWorks instead of AutoCAD

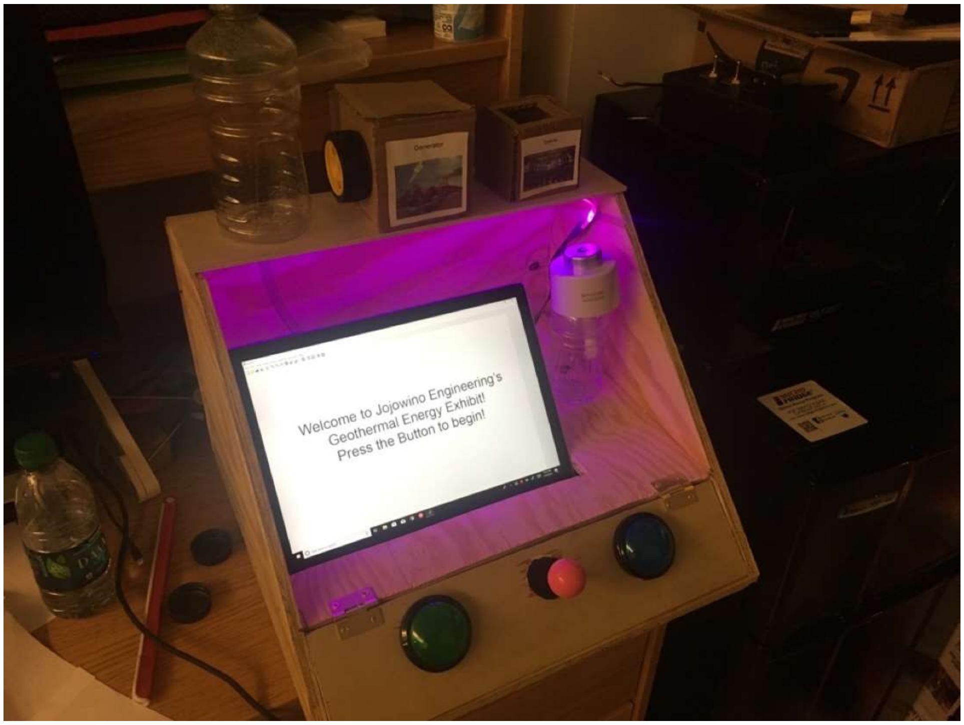


D-17: Our wire diagram for Milestone 4

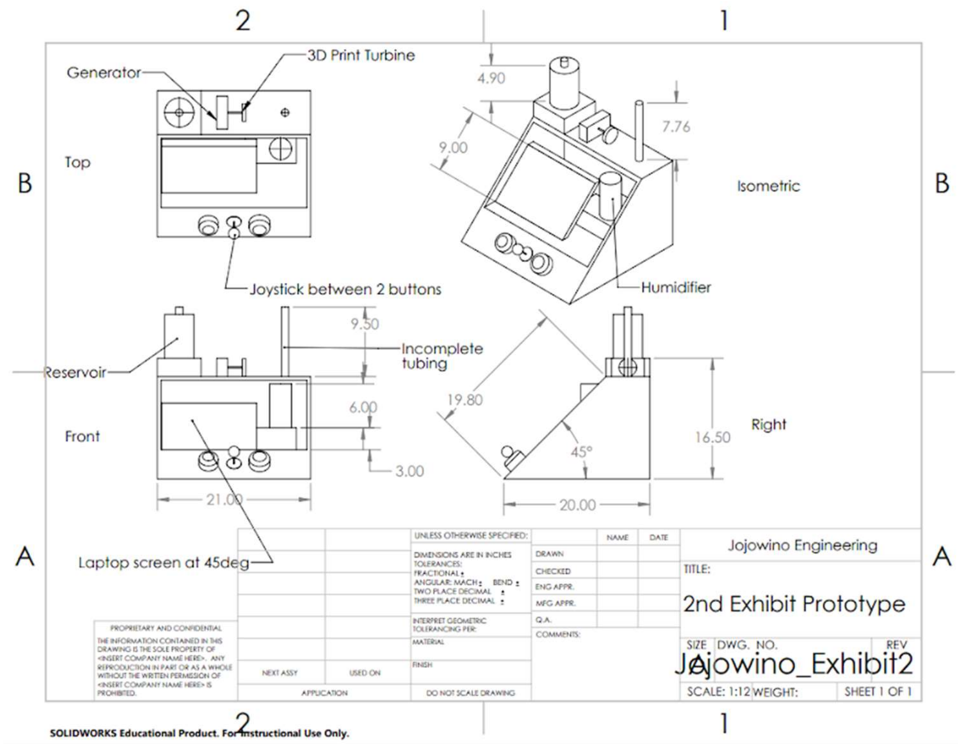
D-18: All of us adding final touches to the finished frame



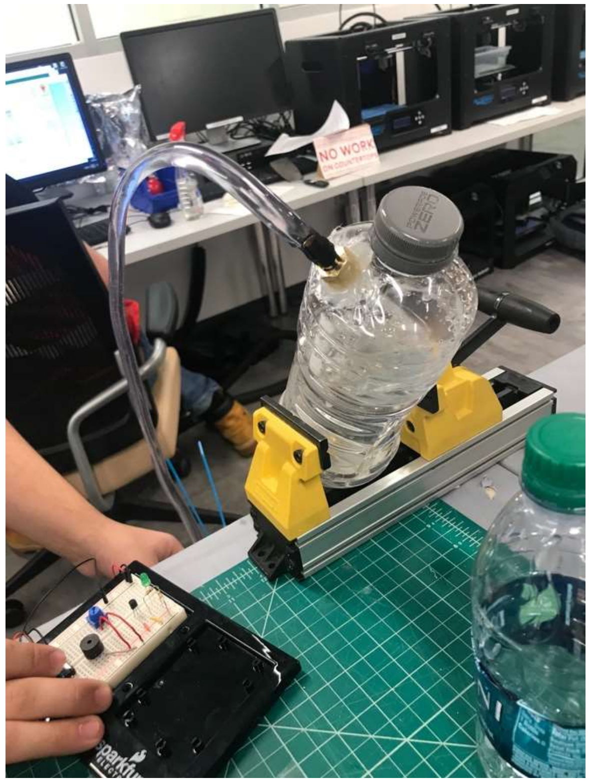
D-19: The wiring as of Milestone 4, outside of the frame



D-20: Our first wood prototype for Milestone 4, complete with an updated, more interactive experience in the form of a quiz game



D-21: Our updated SolidWorks drawing for Milestone 5



D-22: Our first occurrence of a working water loop for the exhibit

D-23: The exhibit's state by Milestone 5


Awesome job! You stopped the Underminer!

What are two things geothermal energy did to fix the Incredi-Drill?

Why is geothermal energy "sustainable"?

Can you think of a way geothermal energy can be used in your own home?

Geothermal Power Plant

Turbine
Generator
Steam
Cooling tower
Hot water
Injection well
1
2
3
4
5

Where Geothermal Energy is Located

200°C
150°C
100°C
0

FUN FACTS!

You've probably seen geothermal energy in action before. Volcanoes and geysers are both natural forms of geothermal energy!

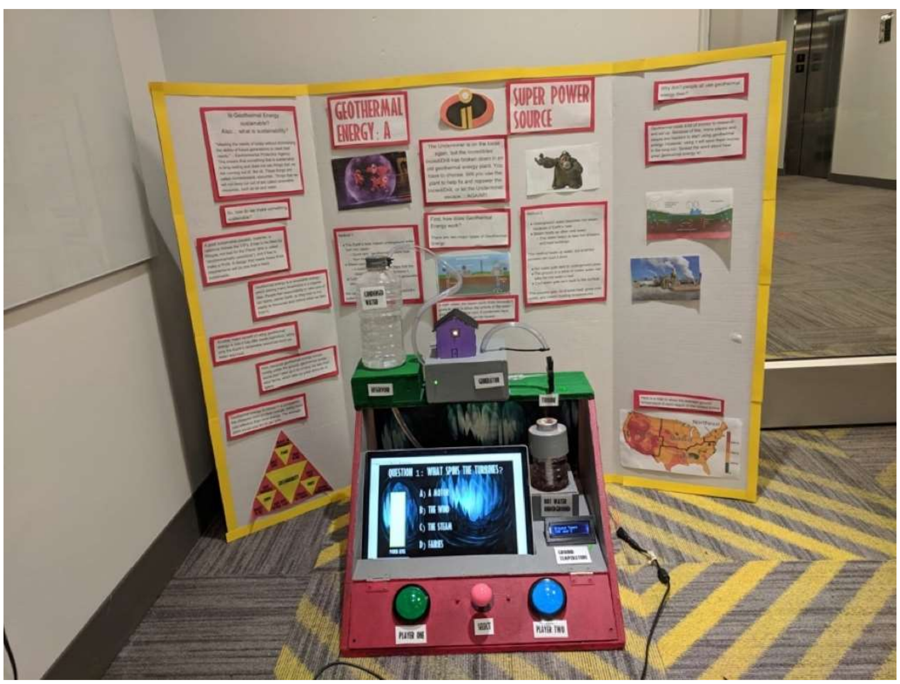
California is home to the world's largest geothermal plant, called the Geysers Geothermal Complex. It is made up of 18 plants!

The United States currently produces the most geothermal power, with more than 3.7 GW going to the national grid.

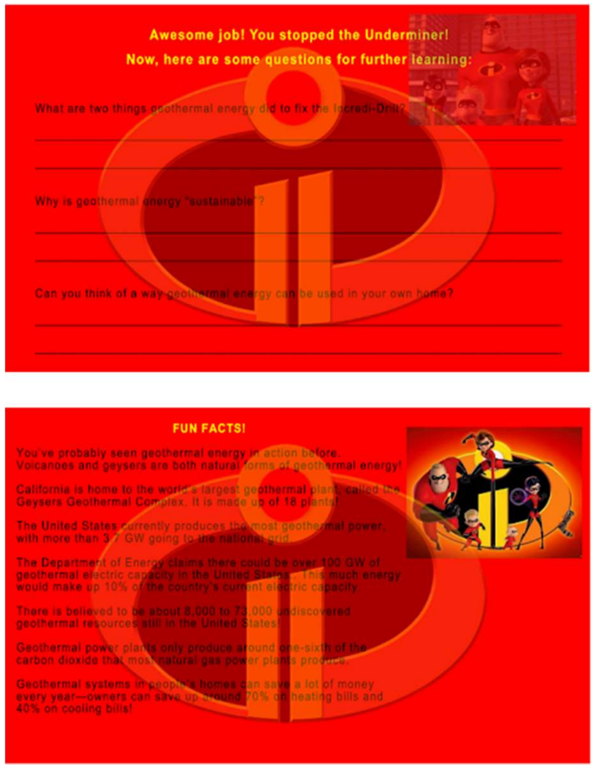
The Department of Energy claims there could be over 100 GW of geothermal electric capacity in the United States.. This much energy would make up 10% of the country's current electric capacity.

There is believed to be about 8,000 to 73,000 undiscovered geothermal resources still in the United States!

D-24: Our original idea for an educational handout

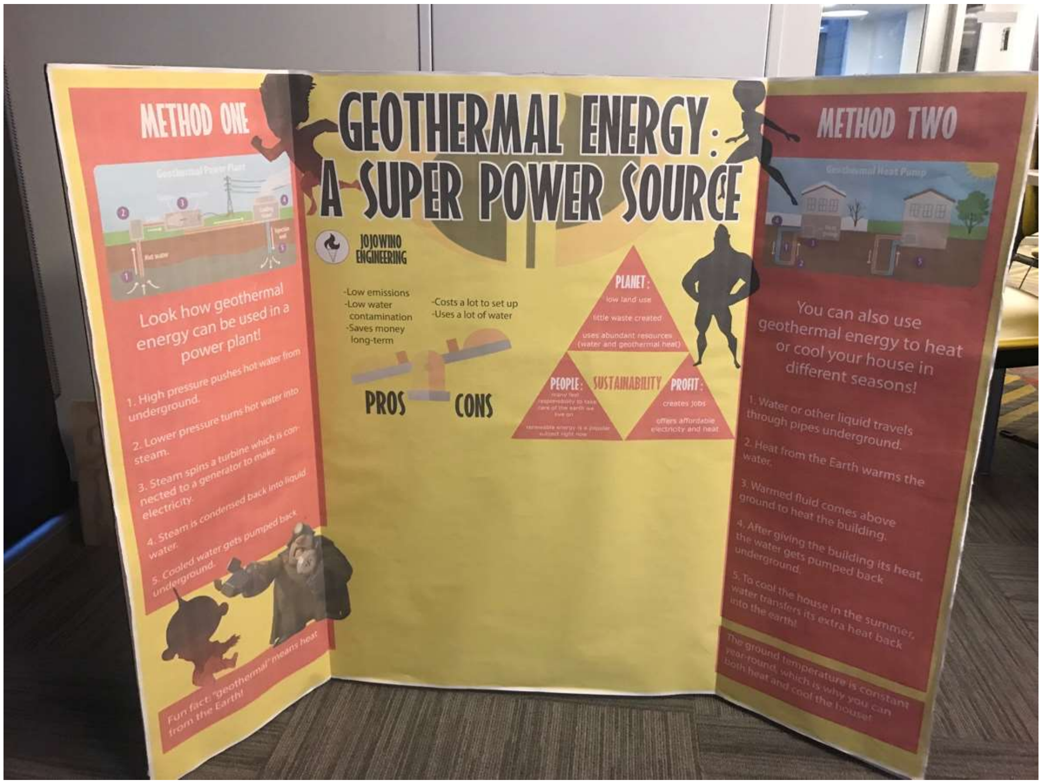


D-25: The exhibit by Milestone 6, complete with our poster up to that point



D-26: An updated handout that is more relevant to the theme

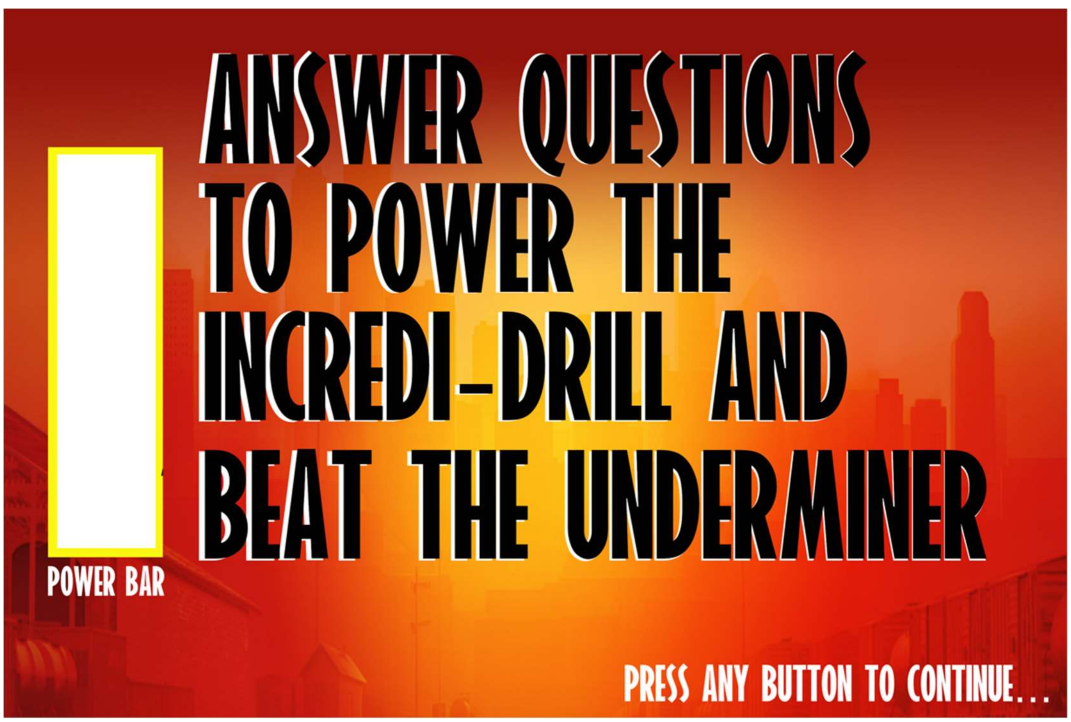
D-27: A glamour shot of our final exhibit on judge walk day, complete with the final poster and the handouts



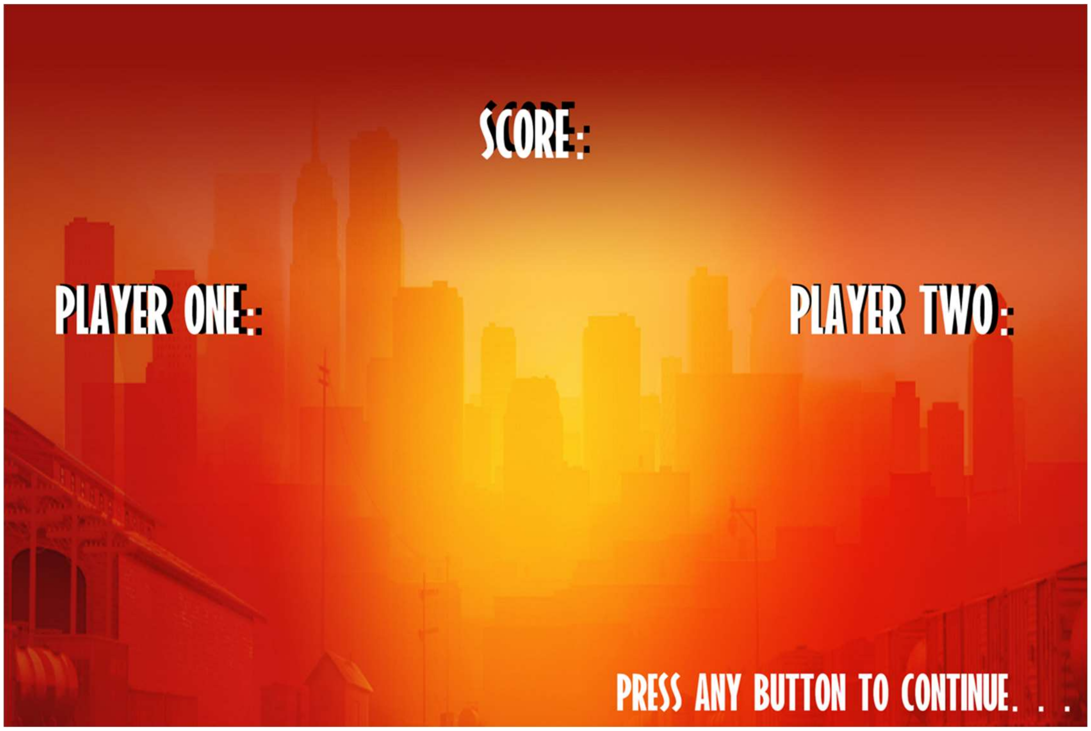
D-28: A picture of our final poster without the exhibit

D-29: Our group proudly standing by our exhibit on exhibition day at the Museum of Science

D-30: Our welcome screen to the game

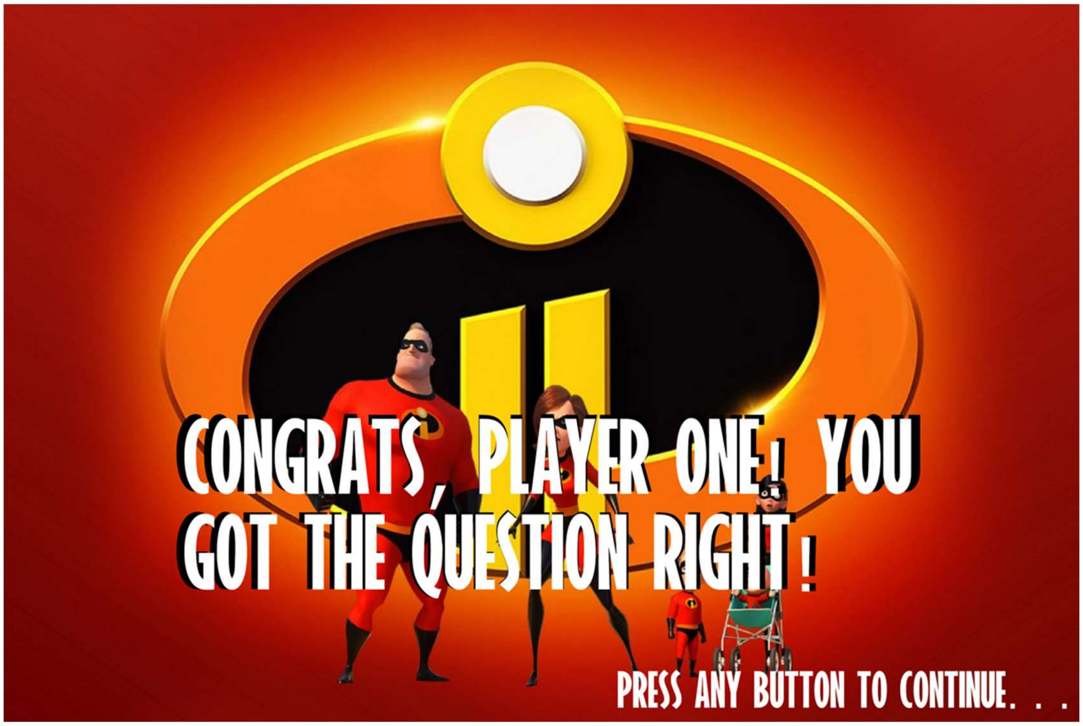


D-31: A screen where we explain the instructions of the game to users



D-32: A screen to display the running score throughout the game

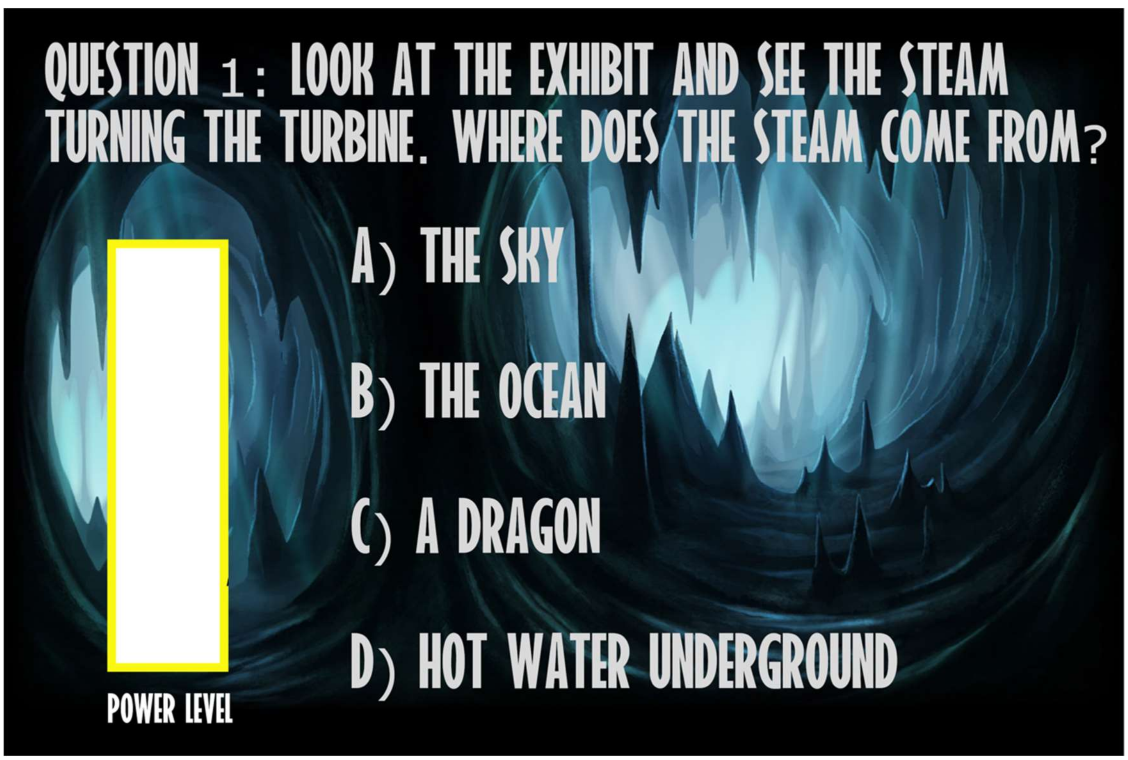
D-33: Indication that player 1 buzzed in first



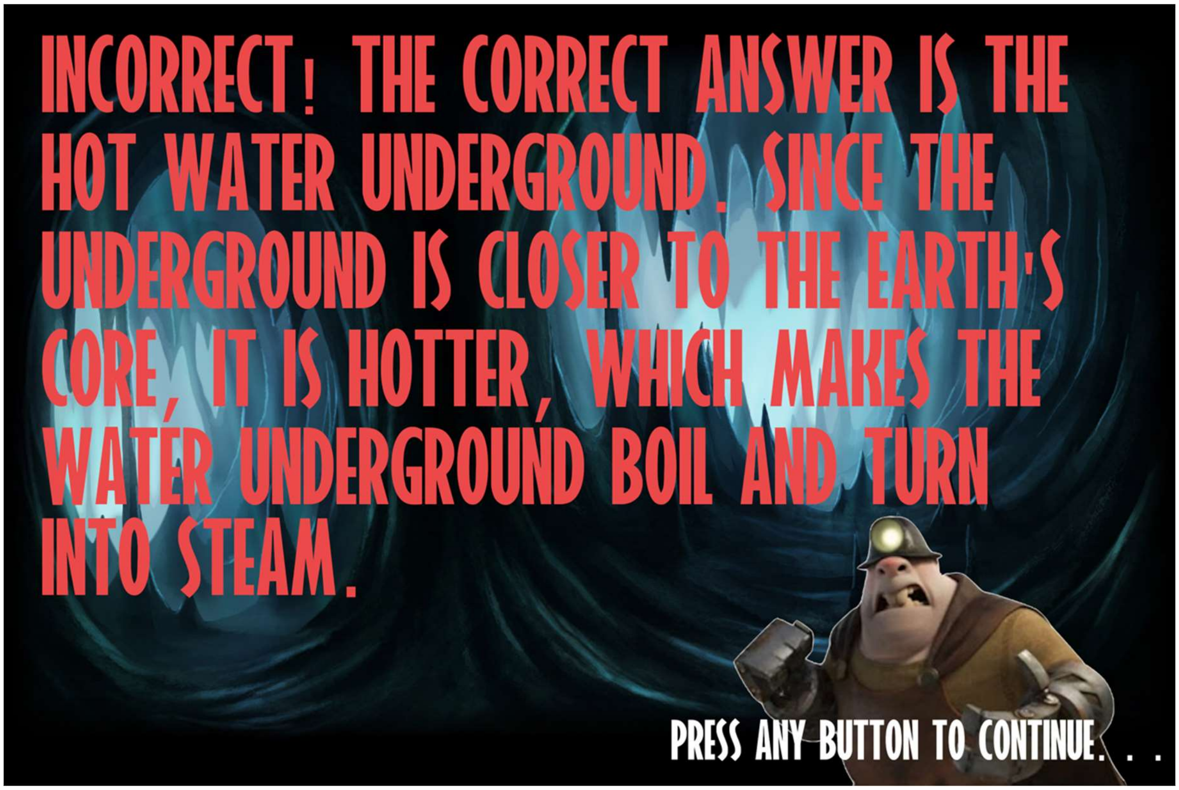
D-34: Indication that player 1 got the question right

D-35: Indication that player 2 buzzed in first

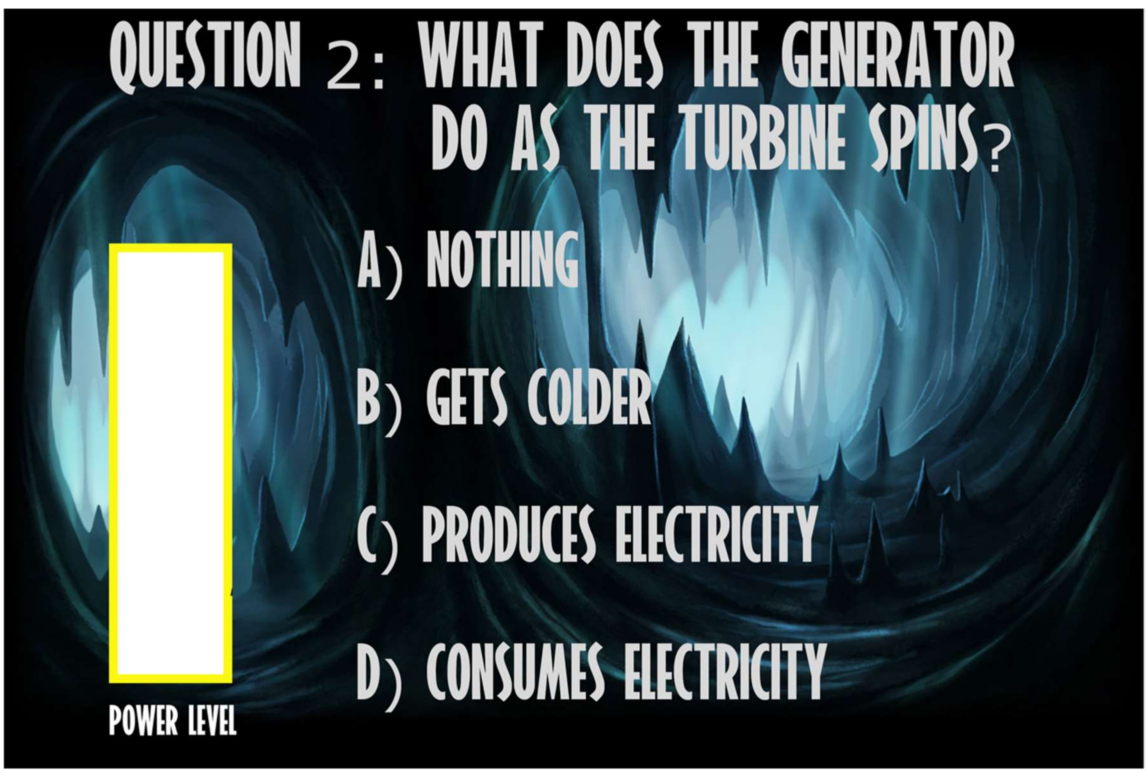
D-36: Indication that player 2 got the question right



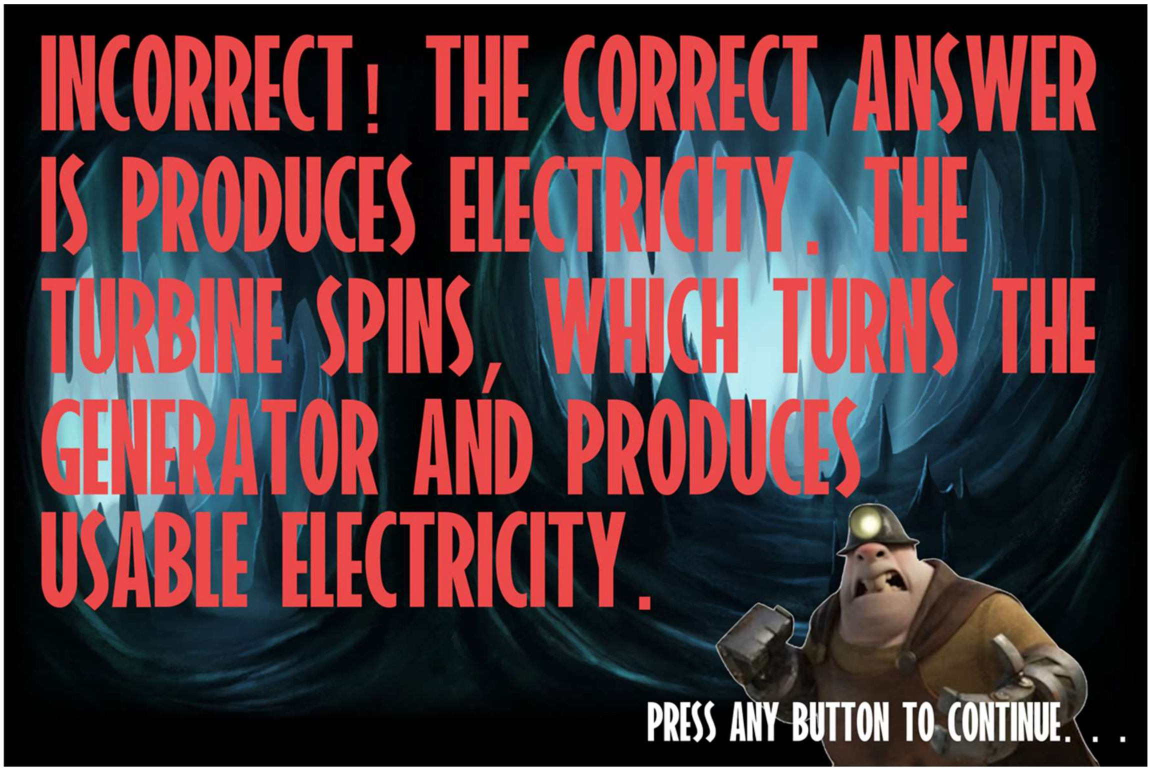
D-37: First question in the quiz



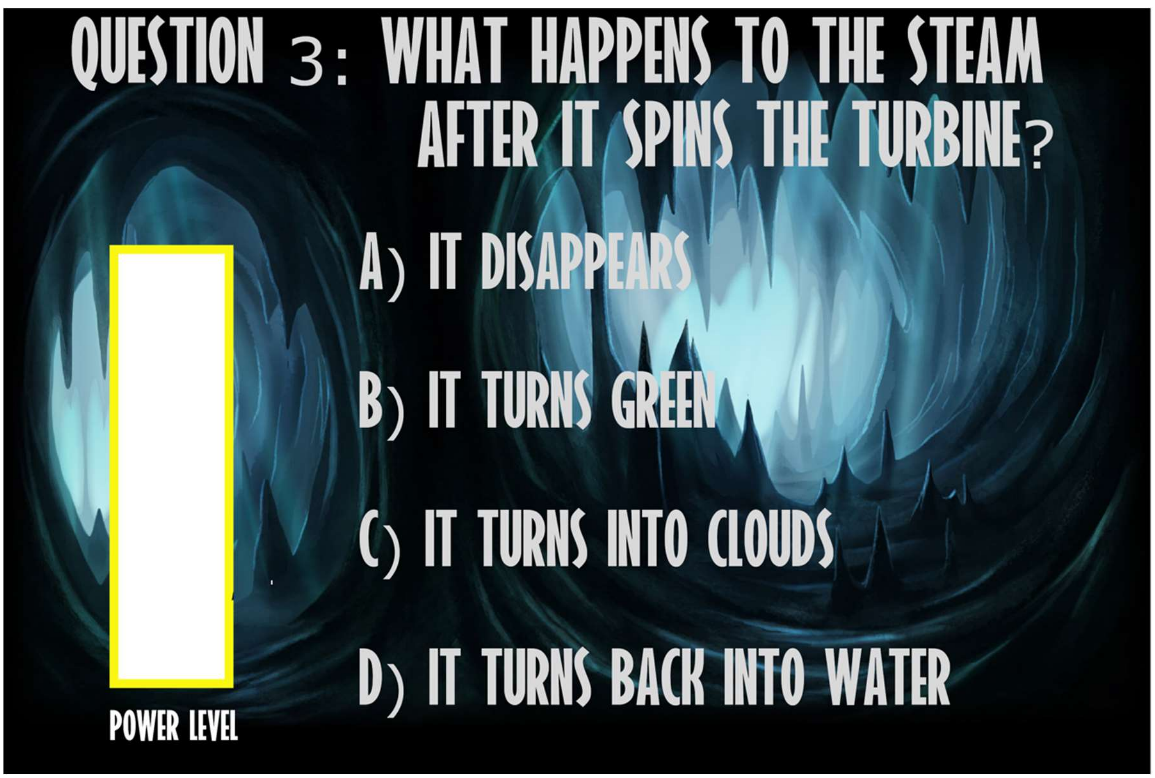
D-38: Explanation if you get the first question wrong



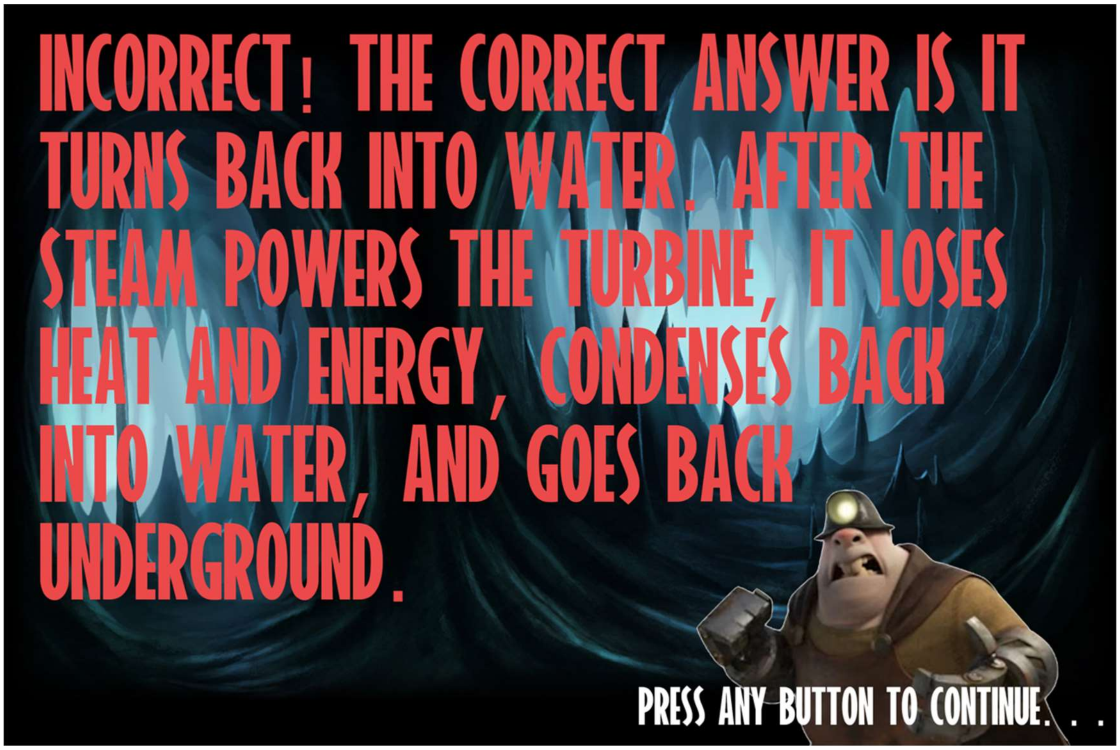
D-39: Second question of the quiz



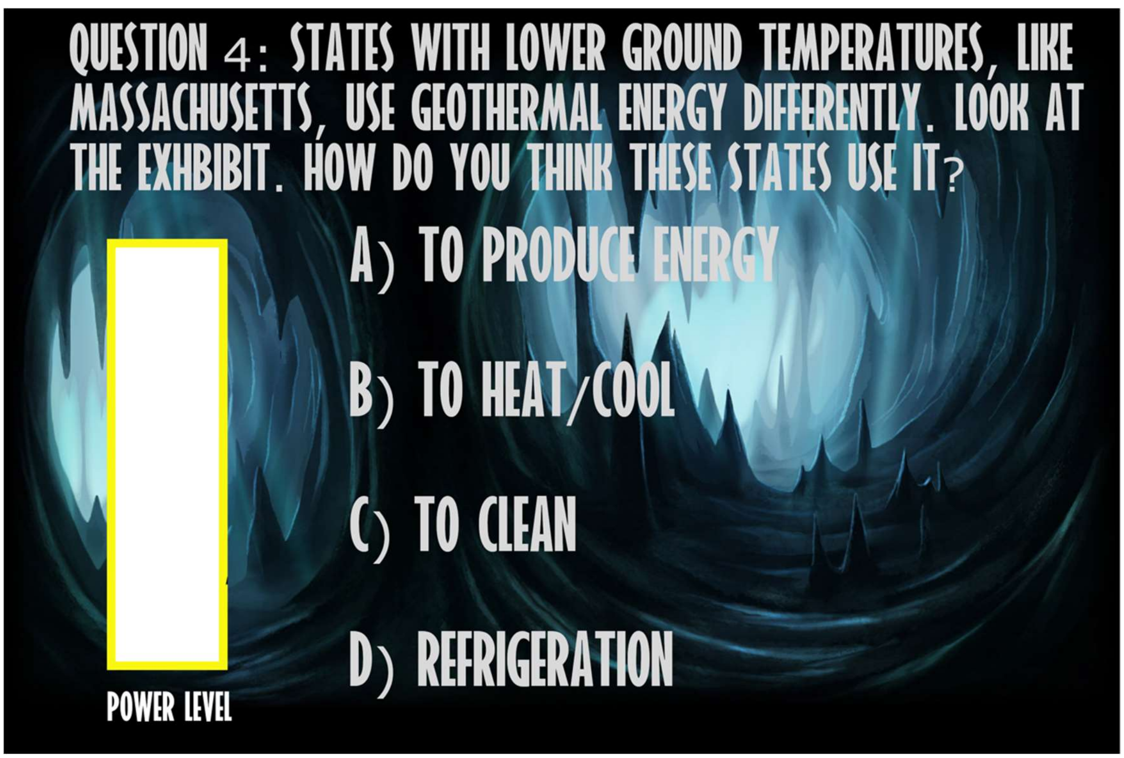
D-40: Explanation if you get the second question wrong



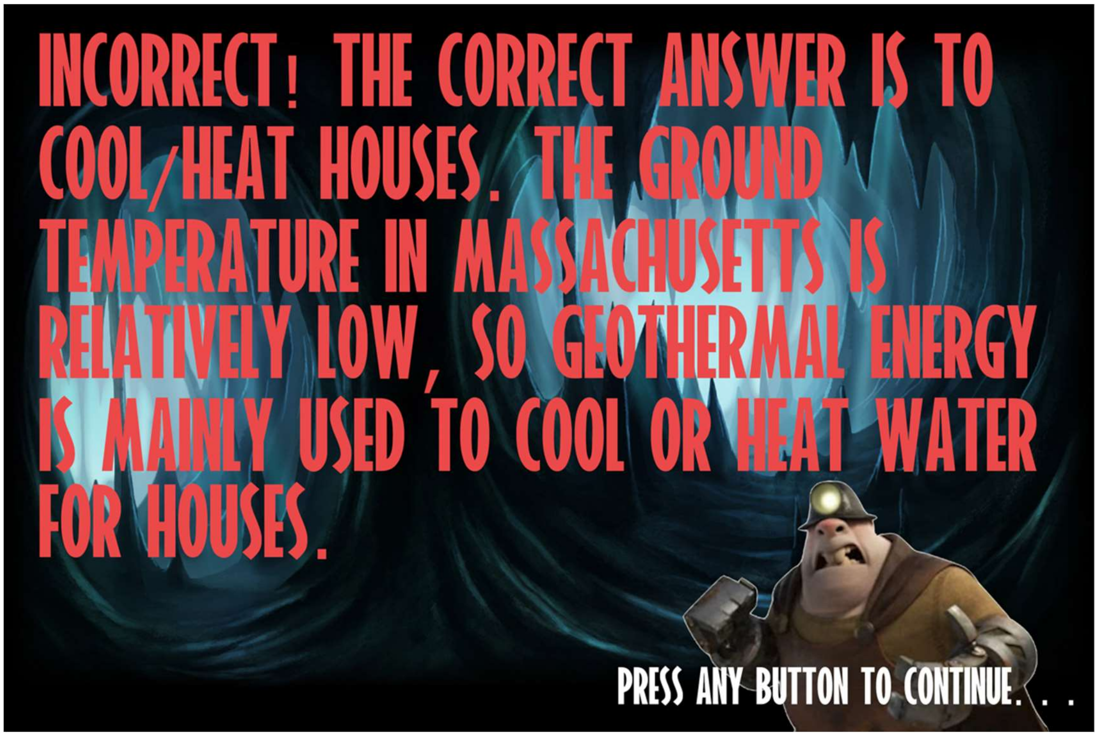
D-41: Third question of the quiz



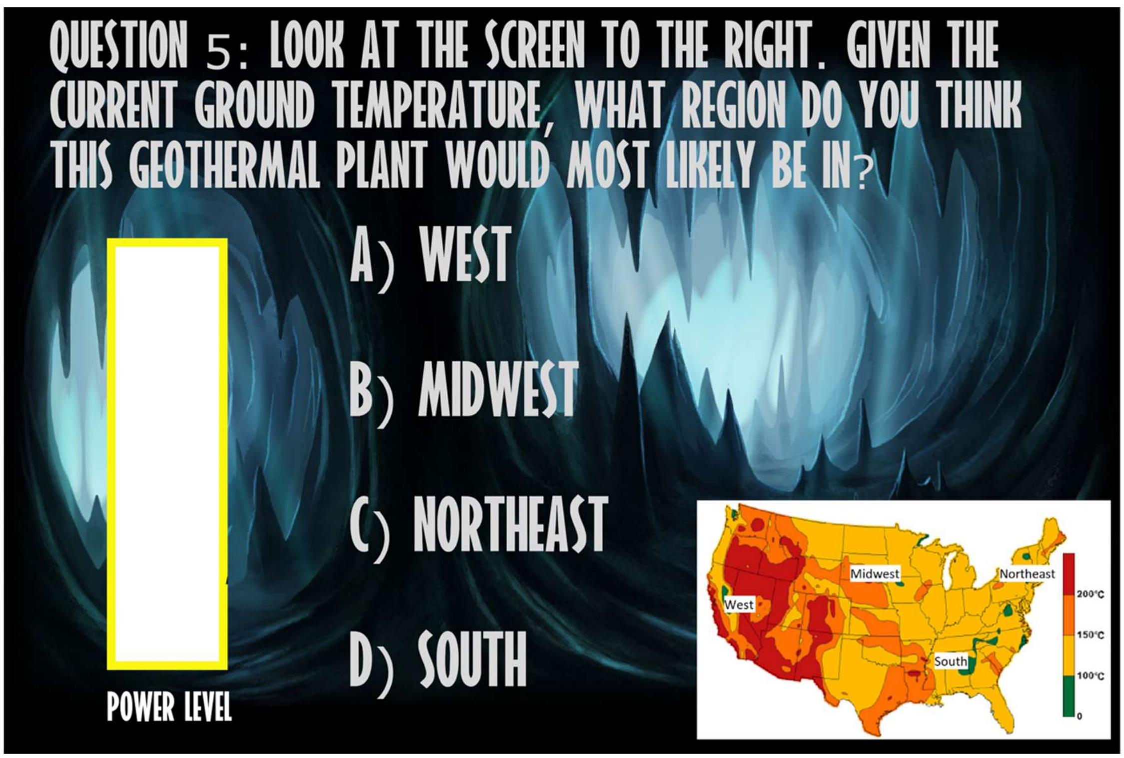
D-42: Explanation if you get the third question wrong



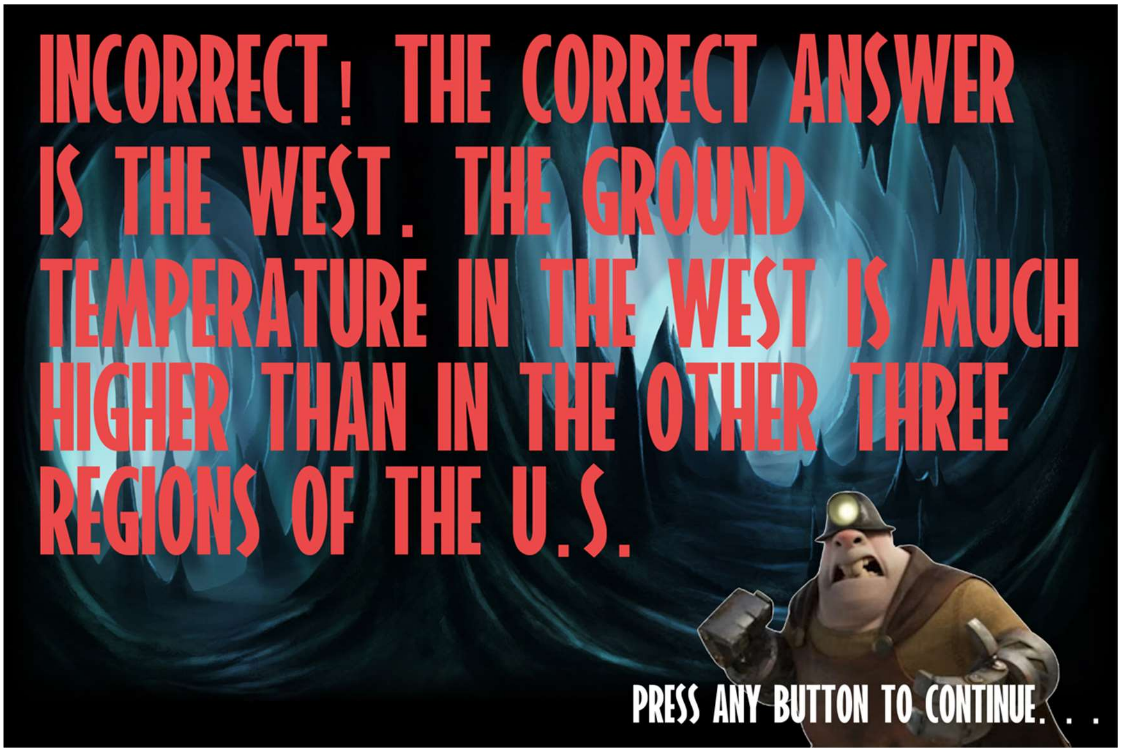
D-43: Fourth question of the quiz



D-44: Explanation if you get the fourth question wrong



D-45: Fifth question of the quiz



D-46: Explanation if you get the fifth question wrong

D-47: Screen to prepare players to redo the incorrectly answered questions

D-48: Indication that player 1 has won

D-49: Indication that player 2 has won

D-50: Celebration screen that both players have defeated the Underminer

APPENDIX I – FINAL GANTT CHART

On the next page, you will find our Gantt chart for the entire project, color coded by Milestone.

(Only Appears in Physical Copies)

APPENDIX J – FINAL BUDGET

	Item	Quantity	Price	In Possession?	Actual Price
Sparkfun Components:	Arduino Mega	1	$ 19.95	TRUE	$ -
	Breadboard	1	$ 3.00	TRUE	$ -
	Jumper Wires	10+	$ 2.00	TRUE	$ -
	RGB LED	1	$ 2.05	TRUE	$ -
	LEDs	5	$ 1.00	TRUE	$ -
	LED light strip	1	$ 20.00	TRUE	$ -
	LCD screens	1	$ 15.00	TRUE	$ -
	Mosfets	6	$ 5.00	TRUE	$ 5.00
	330 Ohm Resistor	5	$ 0.30	TRUE	$ -
	10K Ohm Resistor	12	$ 0.60	TRUE	$ -
	12V Power Supply	1	$ 7.85	TRUE	$ -
	DC jack to screw terminal	1	$ 1.00	TRUE	$ 1.00
	Pump	1	$ 10.00	TRUE	$ 10.00
	Joystick	1	$ 8.00	TRUE	$ 8.00
	Arcade Buttons	2	$ 7.00	TRUE	$ 7.00
Exhibit Components	1/2 inch plywood	12 sq. ft	$ 40.00	TRUE	$ 33.00
	1/8 inch Wood	2 sq. ft	$ 8.00	TRUE	$ -
	USB fog machine	1	$ 10.00	TRUE	$ 10.00
	Paint	1	$ 7.00	TRUE	$ 7.00
	Acrylic	6 sq. inches	$ 10.00	TRUE	$ -
	Hinges	2	$ 1.00	TRUE	$ -
	Tubing	4 ft	$ 4.00	TRUE	$ 4.00
	Powerade Bottle	2	3 Outtakes Points	TRUE	$ -
	Nails/Glue	20/1	$ 1.00	TRUE	$ -
	Miscrosoft Surface Book 2	1	$ 1,300.00	TRUE	$ -
Poster Board Components:	Tri-Fold	1	$ 2.00	TRUE	$ 2.00
	Paper/Color ink	10 sheets	$ 3.00	TRUE	$ 3.00
	Plotter Printer Poster	1	$ 10.00	TRUE	$ 10.00
		Total Price:	**$ 1,497.75**	**Total Actual Price:**	**$ 100.00**

D-51: Our final budget for the project

APPENDIX K – PROJECT HOURS LOG

Milestone	Team Member	Hours	Description
1	Chiaramonte	7.5	Brainstorming, Writing, Peer Review, Duncker
	Durkin	7.5	Brainstorming, Writing, Decision Explanation, Peer Review, Proofreading
	Hodge	7.5	Brainstorming, Writing, Peer Review, Duncker
	Foley	7.5	Brainstorming, Writing, Peer Review, Presentation, Proofreading
2	Chiaramonte	8	CAD Drawing, Research, Sketching, Document Formatting
	Durkin	6.5	Research, Sketching, Resketching, Formatting
	Hodge	8.5	Research, Sketching, Formatting, Decision Making Process Paragraph, Presentation
	Foley	6.5	Research, Sketching, Gantt, Formatting
3	Chiaramonte	9	Flowchart, Electronics Testing, Construction, Updated CAD
	Durkin	10	Presentation Practice, Document Formatting, Construction
	Hodge	8.5	BOM, Construction, Report Writing
	Foley	9	Gantt, Construction, Universal Design Paragraph
4	Chiaramonte	22	Coding, Wiring, Report Writing, Presentation Practice
	Durkin	15.5	Picures log, Report Writing, Buying Wood, Construction
	Hodge	17	Construction, BOM, CAD, Beta Testing Plan
	Foley	17	Changes from M3 Paragraph, Gantt, CAD, Construction
5	Chiaramonte	24.5	Wiring, Water Loop, Programming, Report Writing
	Durkin	15	Pictures log, Poster Design, Report Writing, Question Writing
	Hodge	25.5	Report Writing, BOM, Construction, 3D modeling/printing, GUI Design
	Foley	24	Report Writing, Question Writing, CAD Modeling, Construction, Poster
6	Chiaramonte	27	Programming, Report Writing, Construction
	Durkin	26	Report Writing, Poster
	Hodge	26.5	Report Writing, Construction, Aesthetics
	Foley	27	Report Writing, Poster, Construction
7	Chiaramonte	20	Report Writing, Poster Photoshopping, Wiring final touches
	Durkin	20	Report Writing, Poster Content
	Hodge	20	Report Writing, Poster
	Foley	20	Report Writing, Poster Content
Total	**Chiaramonte**	**118**	
	Durkin	**100.5**	
	Hodge	**113.5**	
	Foley	**111**	
	Total Combined:	**443**	

D-52: Our final time sheet for the project