Inspiring Future Engineers: Teaching Basic Electronics to Create Theremin-Based Musical Instruments

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Abstract

To encourage high school students' interest in electronics and electrical engineering, team projects can be designed that involve adapting and integrating circuits to construct unique musical instruments. The Theremin was one of the first electronic instruments, and has the unusual appeal of being played without touch by interaction with the invisible capacitance fields established around the device's antennae. Theremin circuit designs exist that can be assembled by novices and easily adapted for creative variations in design. The basic principles of electrical circuitry and troubleshooting can be taught to students with no prior electronics experience in a very short time. The students have a direct sense of accomplishment when they can demonstrate a working Theremin-based device and can display their musical talents with a performance while also being able to explain the technical internal functionality. This paper presents several iterations of the Theremin project that have been attempted over the past two decades at a summer science camp for high school students. The most successful designs are showcased along with the teaching methodology that produced them. The project was designed to teach students about engineering research, teamwork, and electrical engineering principles. To assess the outcomes, the journal papers written by the teams of high school students and feedback from former students who are now engineers were analyzed. The student's papers show that every year the project resulted in a circuit that could at least produce sound. The students surveyed overwhelmingly considered the project an influentially positive experience. Former students consistently reported that the greatest impact was not just the electronics education, but also the team engineering experience, which proved beneficial as preparation for a career in engineering.

Introduction

The deficit of scientists and engineers compared with the rising need for experienced professionals in all technical fields reveals a need for stimulating interest in science and engineering with America's youth. Educational programs need to find new and better ways of engaging young minds to foster a desire to explore technical subjects to prepare the next generation of engineers. One approach to cultivate this desire is to design challenging hands-on projects that require teamwork to accomplish the design goals. By emulating the process of an engineering manufacturing team, students can experience the roles of engineers through planning, design, experimentation, building, debugging and creating a finished prototype. Students can fully document the process to produce a written report on the project and give a conference type presentation of their results.

One of the difficulties in developing a project for students is finding a device or system that will inspire interest and reward successful completion of the objectives. A Theremin is an ideal project because of the adaptability of the circuits and the resultant instrument is a unique demonstration piece. The Theremin was invented in the early 1900's by Lev Theremin[1] and patented in 1928 and marketed by RCA. It is considered the world's first electronic instrument. The most unique aspect of the Theremin is that it requires no touch to generate music. The tone and volume are generated by proximity to antennae. The instrument is very challenging to play, but for novices can be fun to explore. The principal behind the operation of Theremin requires understanding the ability of objects to affect capacitance around an antenna. There are several web resources to learn about Theremins, with the most notable being Theremin World.[2] There are many types of Theremin circuit designs shared openly for all skill levels. Some are so small they can fit in an Altoid breath mint tin.[3] For people that aren't electronically savvy, there are commercial Theremins available for purchase. The most noteworthy commercial Theremins are designed and built by Robert Moog; he also offers them as a kit, with the design schematics publically available.[4] With the recent accessibility of Arduinos and other microcontrollers, projects have been designed to make simple Theremins using proximity or light sensors in place of traditional antennas.[5] Theremins can be built for as little as $25 or a high end kit can cost over $500.

The Pennsylvania Governor's School for the Sciences[6] (PGSS) program is held annually at Carnegie Mellon University in Pittsburgh, hosting 50-100 students from across the state. The 5-week program is free for those selected from the 500+ applicants annually, and represents the top science and mathematics students from every area of the state of Pennsylvania. The program is rigorous with mandatory classes held five days a week for 8-10 hours per day. The students have core courses in biology, chemistry, computer science, mathematics and physics, and can take electives in specialized subjects. The students also choose a lab course and a research project in one of the subject areas. For the team project the students only meet for 6 hours per week for 4 weeks; the final week of the program is completely devoted to the team project. The project is prepared by a team project supervisor who is usually a grad student or professor and acts as the expert mentor to educate the students on the project and facilitate their work toward the end research goal. There is also an undergraduate teaching assistant assigned to help the students. In some years the teaching assistant also serves in the role of project supervisor. By the end of the program, the students produce a journal paper on their research topic and must present their work at the program's research symposium.

PGSS has conducted several Theremin based team research projects since 1996. All of the journal articles describing these projects are available online at the archive for the PGSS annual journal.[7] The first PGSS Theremin attempt in 1996[8] used a Theremin circuit described in the November 1967 issue of Popular Electronics[9]. The method required etching a circuit board and soldering. The assembled device had functioning pitch and volume circuits, but the volume antenna interfered with the pitch antenna, so it was reconfigured to be a fixed volume, variable pitch Theremin.

The second PGSS Theremin in 1998[10] was based on an analog design published by Ken Skeldon et al. at the University of Glasgow in the American Journal of Physics.[11] This effort resulted in a nearly functional Theremin, except without volume control due to issues with the volume circuit. In 1999, PGSS students attempted to build a digital Theremin[12] based on a Schmitt trigger chip and logic gates which also appeared in the Journal of Physics article by the group in Glasgow.[11] This design used integrated circuits to process the waveforms, and like previous attempts the pitch circuit was successful but the volume circuit never functioned correctly.

For the 2000 Theremin team project[13], two designs were attempted: digital and analog. The digital team used the Glasgow digital schematics from the 1999 team project and the students were able to identify a design flaw published in the Journal of Physics schematic that prevented the volume circuit from functioning for the 1999 Theremin project. They confirmed the schematic error with one of the authors of the Glasgow paper. The analog device was built from the "144 Theremin" design created by Arthur Harrison[14]. Both the digital and analog Theremins were completely operational by the end of the five week program. Of the two designs, the analog provide to be more robust and easier to build. One notable design difference that helped these efforts succeed compared to prior years was building the circuits on breadboards for the final product. In previous attempts, soldering was a major hurdle to debugging and repairing faulty circuits.

To build on the success of the 2000 analog Theremin, the schematic was modified for the 2003 team project with a summing circuit to merge two pitch circuits. The volume antenna was replaced by a variable resistance foot pedal. The double pitch Theremin was another complete success. [15] In 2006 the PGSS Theremin project took another leap forward by designing a triple pitch Theremin with three antennae (to be played with two hands and a head).[16] To make the project more interesting, a laser component was introduced to attempt integration of a laser piano. A laser source was aimed at a photoresistor, and when the beam was interrupted a single pitch was generated. A series of these lasers assembled in parallel lines form a laser piano. In 2008, the Theremin portion was dropped and the students constructed laser piano modules, using aspects of the 2006 Theremin design and attempted to solder all components instead of using breadboards.[17] The most recent Theremin project was attempted in 2013 and produced a fully functioning Theremin[18] using a simple analog design mimicking the modules of the original RCA Theremin.[19]

All of the student journal articles with specific schematics and details of each design can be found free online at http://sciences.pa-gov-schools.org/journals in pdf format. A breakdown of the project group sizes each year and gender breakdown is shown in Table 1; the group size ranged from 6 to 11 students, with an average size of 8.25 students and for five of the eight years the groups were 50% or more female with the average group being 48.5% female. The gender balance is surprising since most females in the PGSS program gravitated toward biology and chemistry projects and often left mathematics, computer science, and physics projects with a minority of females. Other demographic information such as race, educational and/or economic background is not available since the projects studied span back 20 years and that data was not retained, nor can it be gathered easily now since contact information is not available for many of the participants.

Table 1. Theremin team project size and composition at PGSS

Year	# of students	# female
1996	10	6
1998	6	3
1999	6	4
2000	10	5
2003	6	2
2006	11	4
2008	8	3
2013	9	5
Total	66	32
Average	8.25	4

Teaching Methods

The majority of the students who worked on these projects had no electronics experience and few had any knowledge about Theremins. The first week of meetings (6 hours) was spent introducing the fundamentals they need for the project. They learned a brief history of the Theremin and the capacitance principles that allowed a hand to interact with the antenna without physical touch. They learned the meaning of voltage, current, Ohm's law, capacitance and inductance. Students were taught series and parallel circuit elements with resistors, capacitors and inductors and shown corresponding circuit diagram symbols. They were given breadboards and simple activities connecting components in series and parallel and checking their resultant values with multimeters. They were shown how to transfer circuit diagrams onto breadboards and given graph paper to help them lay out their components. The process of transferring a circuit diagram to a breadboard can be challenging for a novice. By introducing the intermediate step of laying out the components on a paper breadboard pattern using pencil, it was easy for a student to adjust the layout and get feedback from the teacher, as seen in Figure 1. For the 2008 project which attempted a return to soldering circuits, PC boards were purchased from Radio Shack that matched the connections of the breadboard the students used for laying out and testing their circuits (Figure 2). Students were individually assigned one or more subsystems of the Theremin to convert from a circuit diagram to a breadboard layout. Every subsystem was assigned to each least two students so that there was more than one person who has studied each portion of the schematic. Students were also assigned topics for a literature search in preparation for writing a journal article on the project.

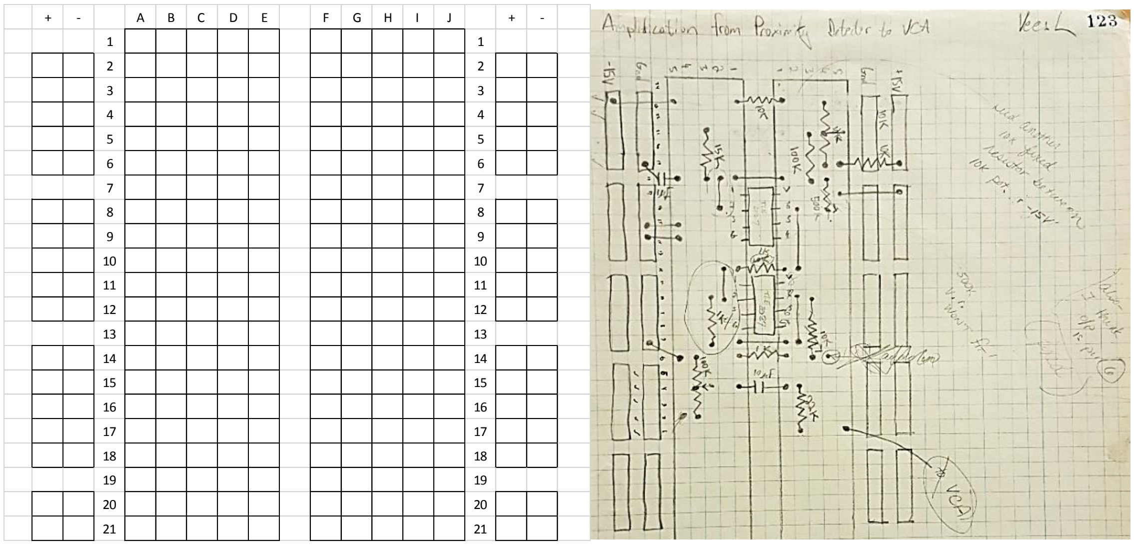

Figure 1. Excel (left) or graph paper (right) breadboard pattern for component layout

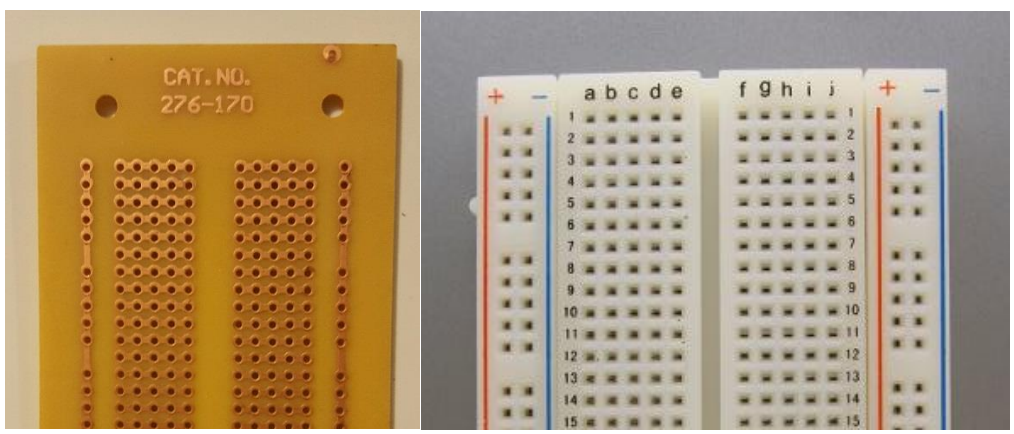

Figure 2 Printed Circuit board (left) corresponding to a breadboard layout (right) for easy transfer for soldering.

In the second week, more complex concepts were presented. Students learned about signal theory starting with wave properties, then observe demonstrations of waveforms using function generators and oscilloscopes. They were given time to experiment using the lab equipment. They learned the basics of operational amplifiers and integrated circuit chips if they were building a digital Theremin. Segments of the Theremin design were discussed and subsystems (fixed oscillator, variable oscillator, mixer, amplifier, voltage control) were described by their function and interaction with connected parts. Expected DC and AC outputs of each subsystem were determined for troubleshooting purposes. The principle of heterodyning was introduced using the concept of beat frequencies, and described in the context of the high frequency fixed and variable oscillators. With the aid of two function generators and a two channel oscilloscope with math functions, heterodyning can be visualized. The breadboard circuit layout homework was peer reviewed; all students who transferred a particular subsystem to graph paper exchanged their layouts and check them against the original diagram. The instructor also reviewed them. The best error free layout for each subsystem was chosen for the project and students begin populating the board. The literature search results were shared, and additional topics were assigned if necessary.

By the third week students were already assembling their circuits on breadboards. The actual circuit assembly does not take much time compared to the troubleshooting and integration of subsystems that followed. They worked in small groups of two or three students assembling and double checking the schematics and began the troubleshooting process. Work groups should be small and modular, much like working on a professional engineering team. Keeping size down allowed everyone to get hands-on (Figure 3). At the most basic level they would compare the assembled circuit to their designed layout or original circuit diagram. At a higher level they would follow voltages/signals through the circuit with a multimeter or oscilloscope. Each of the four oscillator circuits needed for pitch and volume heterodyning should produce a high frequency output and many Theremin designs specify the typical frequency and voltage of this signal. An oscilloscope was used to visualize the high frequency heterodyning process that created the oscillation in the audible range. The voltage regulator could be checked for the correct DC voltage output. The students also planned the Theremin enclosure and the user interface (antenna, knobs, buttons, switches and jacks) and created a parts/materials list for the materials needed. The most complex circuits were assigned to the most advanced students and the simpler ones given to the students who are struggling so that everyone was sufficiently challenged with minimal frustration. The students who finish their circuit first were reassigned to work on the paper, presentation or the enclosure design/construction.


Figure 3. PGSS 2000 students: working on a digital Theremin circuit (left), analog Theremin team showing off their finished instrument in clear Plexiglas (right)

Circuit integration began in week four. A representative from each circuit was assigned to the systems integration team to get each working circuit functioning with the others; the pitch variable and reference oscillators must be combined and tested to ensure proper heterodyning. The volume oscillators need to be tested in the same manner. The voltage regulator can be attached to the mixer. Some circuits may need transferred onto new breadboards if space needs to be minimized. Those who aren't on the integration team were assigned to the enclosure and interface construction. Plexiglas and wood have been popular materials since they were readily available and easily cut and drilled to construct an enclosure for the circuits. Throughout this process, elements of the engineering design cycle are used, but were not explicitly taught. More emphasis was placed on understanding the technical drawings, translating them to a circuit, effectively troubleshooting, testing for optimization of settings, and if there was time, making design modifications and augmentations.

In the final week the students had every day dedicated to the project, unlike the previous week where they only met twice a week for three hours each time. Their main goal was to prepare a journal report on the design and construction of the Theremin while completing the device. They finish final debugging and construction of the enclosure. Any design changes or adaptation were documented. If they produced a working pitch or volume circuit they characterized the response by mapping the pitch or volume level compared to distance of a probe from the antenna. Students devised a method using an optical bench and mounting a horizontal rod with an adjustable distance to interact with the antenna for mapping the frequency response of the instrument (Figure 4). By moving the rod closer to the antenna in increments, an oscilloscope could capture the frequency or volume (voltage) level of the output. The frequencies could be graphed (Figure 5) or mapped onto the musical scale to determine octave range of the instrument. Front panel adjustments and room conditions could alter the musical or volume range. The students also prepared a PowerPoint presentation for the research symposium at the end of the program.   Students also practiced their Theremin skills to perform a song at the final presentation. One particularly masterful Theremin player was able to take requests during the presentation and play passable versions of the songs suggested. After the program the Theremins remained at Carnegie Mellon University. For many years they sat in a glass display case in a physics lab, with informational fliers posted behind them, educating countless undergraduates on the concept of a Theremin.

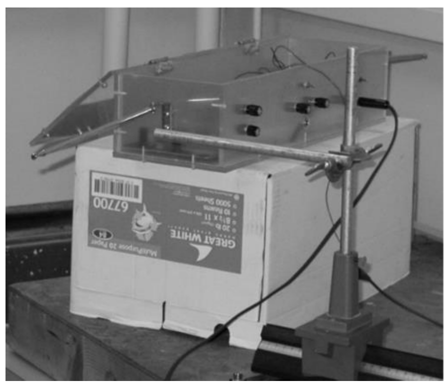

Figure 4 measuring the frequency response as a function of distance from the antenna.

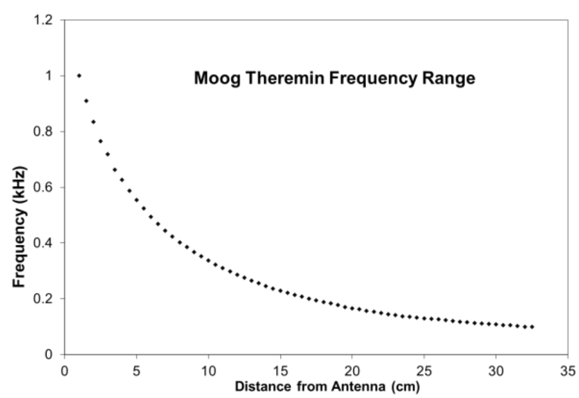

Figure 5 A graph of the frequency response of a commercial Theremin measured by students[15]

At the PGSS program, the most commonly used Theremin designs for the projects have been Arthur Harrison's 145 Theremin (or its predecessor, the 144 Theremin)[14] and the designs for the analog and digital Theremin published in the Journal of Physics by a group at the University of Glasgow.[11] The Harrison design has been reliable, but the Glasgow designs have been troublesome, especially for volume control. For a sense of scale of the project, the entire 145 Theremin schematic is shown in Figure 6.

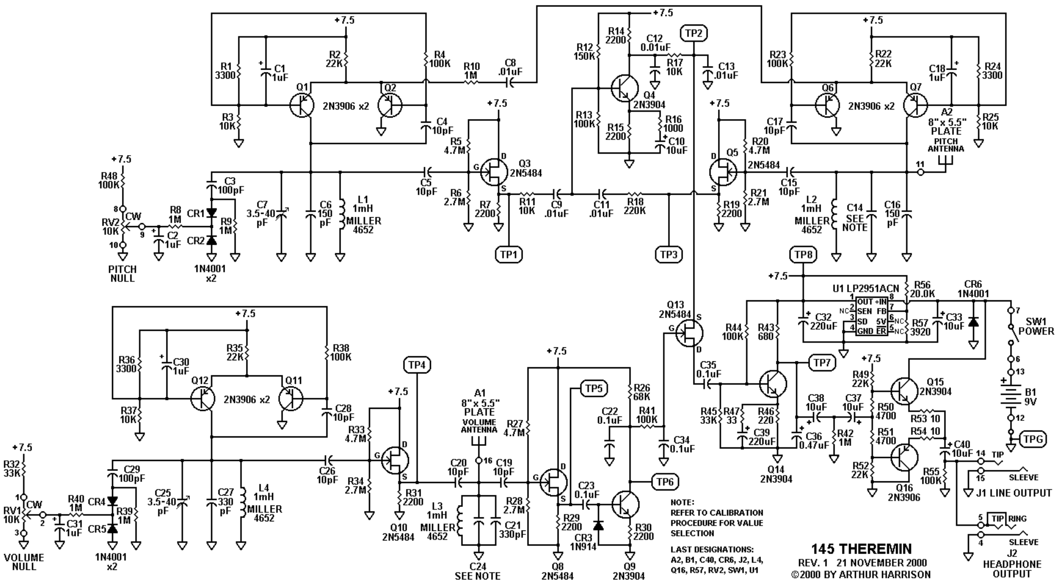

Figure 6 Arthur Harrison's 145 Theremin design schematic.[20] A modularized form of this circuit used for dividing the project in sub-assemblies can be seen in the PGSS 2000 Theremin Report.[13]

Learning Outcomes and Analysis

The Theremin projects were designed to achieve several educational objectives. On the surface the project introduced specific engineering content, taught basic electrical engineering principles and allowed students to apply them to a practical application. On a more general level, the projects were an introduction to research, to understand the scientific/engineering methodology and produce a journal type paper and conference presentation on their project. Secondly the projects required students to work in teams to experience the collaborative research and development environment. The Theremin team projects incorporates all of these learning outcomes and fit well into the framework of an advanced academic summer program.

The outcomes can be assessed using two sources of data. First, the journal articles written by the students are a testament to their level of technical competence achieved and their understanding of research and the electrical engineering concepts assimilated. Second, alumni of the project were contacted via email (with IRB approval) and asked "Could you write a few sentences about what you learned on the project, and any impact it had on your academic choices? (please also include your degrees earned and current or recent job titles)". From their written responses, the educational benefit can be assessed qualitatively by examining their perception of the impact of the research exposure, teamwork, and technical skills in hindsight.

In the analysis of the students' journal articles, each team's project was assessed based on their technical level of success to determine if they were gaining competency in the engineering design, construction, and debugging concepts taught. Also the changes to the project throughout the years are noted to show the evolution of the teaching approach and modifications to the technical approach to Theremin building. For the written responses from students, a qualitative review is performed to identify the most common themes and comments by students which can be generalized to the larger population. The credentials of the respondents will also be considered since their continued studies in engineering or science give them professional credibility to comment on the importance of the project and its effectiveness for influencing their chosen career path.

Results

Over the eight Theremin related projects at PGSS, varying levels of success have been obtained with regards to a fully functioning device (Table 2 and Figure 7 through Figure 11), but each team achieved at least partial functionality. The level of success of each project is evidence of the achievement level of each team. In all cases, the students achieved some level of circuit functionality showing they gained a deep enough understanding of the subject material to read a circuit diagram, lay out the schematic on a breadboard, then build and debug an electronic device. Lessons on the educational methods were learned with each iteration. Soldering is very time consuming and novices often damage components. This makes troubleshooting and fixing mistakes very difficult. The projects were much more successful after solderless breadboards became the platform for circuit construction starting in 2000. Student still learn to solder when creating the interface and attaching wires to antennae, switches, knobs, and jacks. Analog circuits seemed easier for the students to understand and build since integrated circuit chips can be a black box that are harder to conceptualize unless simple models exist. Students learn that by breaking a large engineering task down into smaller pieces it becomes manageable and comprehendible.

Table 2 Summary of Theremin Designs and Performance Results

Year	Type of Theremin	Level of Success	Figure #
1996	Vintage design from 1967 Popular Electronics magazine, soldered	Functional pitch circuit, volume circuit non-operable and replaced by volume knob	Figure 7
1998	Analog design (University of Glasgow), soldered	Functional pitch circuit, constant volume but volume control was non-functional.	Figure 7
1999	Digital design (Glasgow), soldered	Functional pitch circuit, volume control was non-functional.	Figure 7
2000	Two Theremins (“Harrison 144” analog and “Glasgow” digital design), breadboard construction	Both devices were made fully functional, pitch and volume antennae/circuits worked on each device.	Figure 8
2003	Analog Theremin (“Harrison 145”) with two 2 pitch circuits, volume pedal, breadboard construction	Both pitch circuits worked and mixed well, volume pedal had reasonable performance.	Figure 9
2006	Analog Theremin (“Harrison 145”) with 3 pitch circuits, and 3 laser piano keys, breadboard construction	All three Pitch circuits with antennae functioned. Each pitch could also be switched to be triggered by a laser interrupt. Volume knob replaced antenna.	Figure 9, Figure 10
2008	Five key laser interrupt piano modules, pitch tuning knob, soldered circuits, in project boxes adapted from Theremin circuits and other sources	Expanding on the laser keyboard design from 2006 was successful to make a working 5 key module with soldered components.	Figure 10
2013	A basic analog design using breadboard construction	The pitch circuit was fully functional but volume control was non-responsive and replaced with a variable amplifier.	Figure 11

Figure 7. PGSS Theremin projects: 1996 (left), 1998 (center), 1999 (right)

Figure 8. PGSS 2000 Theremin projects, analog in Plexiglas (left) and digital in the wood case (right)

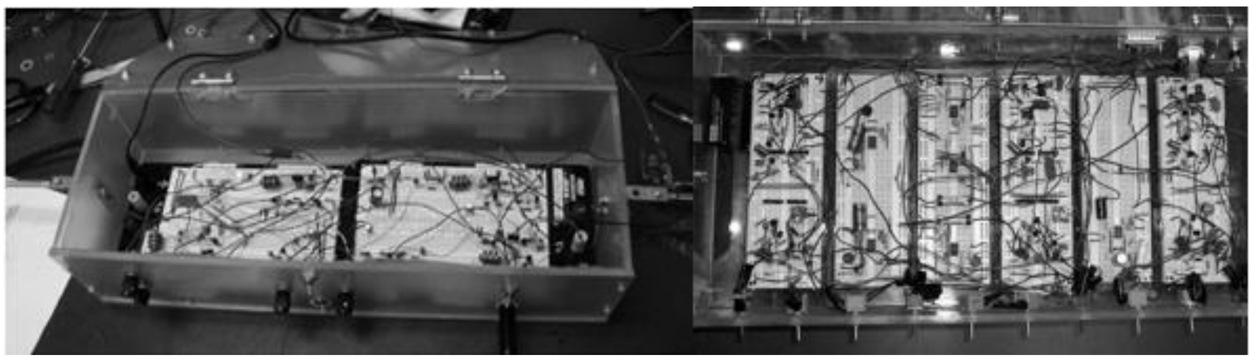

Figure 9. PGSS 2003 dual pitch Theremin (left) and 2006 triple pitch Theremin (right), both in Plexiglas

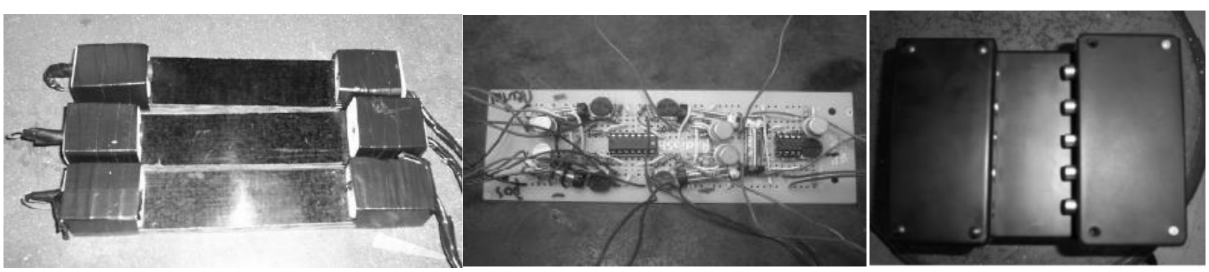

Figure 10. PGSS 2006 three laser piano key option on Theremin (left) PGSS 2008 condensed circuit design for a stand-alone laser piano (center) and the five key version of the device using that circuit (right).

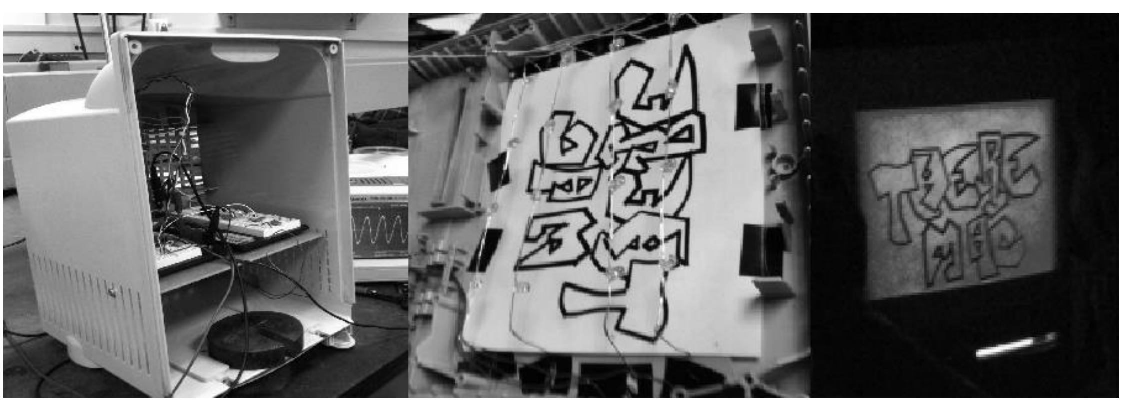

Figure 11. PGSS 2013 “ThereMac,” analog Theremin built in the housing of a 1993 Color Classic Macintosh with an LED illuminated decorative screen

An email was sent out to students who had worked on the project (48 of the 66 students had emails on file, but there was no information on whether they were active email addresses) and they were asked to share their memories of the Theremin project and if it had an impact on their academic or career choices. They were also asked to share their degree completion status and current job title/employer. The survey was IRB approved. Of the 48 emails sent, eight former students replied representing the five most recent projects. These are portions of their responses:

*Male Student, PGSS 2000 Project: "*The team project was one of the most impacting and indelible memories of the entire session of PGSS. Throughout secondary school, I worked on science and engineering projects, but the particular PGSS physics team project -- the analog Theremin build -- was a uniquely challenging experience for me as it involved technical, engineering, and team-based attributes. The technical aspects were intellectually stimulating: reading and interpreting complex electrical diagrams in an effort to understand each component's function was beyond anything I was tasked to do in my schooling. The engineering trials played into my desire to pursue a post-secondary engineering degree. There were many occasions when the expected results differed from reality and we had to pursue different (and outside-the-box) solutions to achieve success. Working together in a team setting was necessary (though sometimes difficult) in order to accomplish the many sub-tasks within the exceptionally short project time. Altogether, the amalgam of technical, engineering, and team-based attributes made the experience rewarding in ways that wouldn't fully manifest until later in my post-secondary, graduate, and professional career." *Highest degree earned: Ph.D. in material science, University of Pittsburgh. Job title: Senior Scientist -- Tissue Engineering: Biomechanics at Ethicon Endo-Surgery*

Female Student, PGSS 2003 Project: This project was the first time I ever had to apply a theoretical equation to build a concrete, physical phenomenon...I had learned equations as theoretical concepts expressed algebraically, nothing more. Simple as it sounds, it was a strange mental leap, the experience of plugging real numbers into those symbols, and seeing the resulting numbers confirmed by an oscilloscope. *Highest degree earned: M.S. in aerospace engineering, MIT. Job title: Software Systems Engineer at Jet Propulsion Lab*

Male Student, PGSS 2003 Project: …the deeper, and more meaningful, lesson was this -- learning to work and accomplish something (designing a complex system) as a team. At the time, I was already pretty set on aerospace engineering (in which I'm pursuing my Ph.D. now), and the Theremin project was another step in helping me grow both as an individual student and as a team player. *Highest degree earned: B.S. mechanical and aerospace engineering, Cornell. Job title: Ph.D candidate at Georgia Tech*

Male Student, PGSS 2006 Project: "I was very nervous and scared with the circuit components because I'd always had trouble with labs…but as time went on and with heavy guidance from [our team project leader and TA], I found out they weren't that scary and that I could totally do it. I also remember feeling particularly relieved one day when [the team project leader] came over and plugged in our audio circuit all the way after it hadn't been working [a faulty loose connection], and he said "an expert is simply someone who's made all the mistakes." That's something I think about to this day and pass on to my students… not only did I successfully complete my component of the project, which was the laser interrupt module, but at the end of the program I even ended up heading to RadioShack to buy some components and a breadboard to play around with circuits on my own. In my mind I have always classified that project as the very last piece of the puzzle that convinced me to be an EE major in college…[the Theremin] convinced me I could succeed in the breadth of the subject." *Degrees earned: B.S. in electrical engineering, Princeton University. M.S. in electrical and computer engineering at Duke University, currently a Ph.D. candidate at Duke University in electrical and computer engineering under an NSF Fellowship.*

Female Student, PGSS 2008 Project: "The PGSS Theremin project was the single most impactful experience in turning me into an electrical engineer…I thrived in the collaborative work environment and became close friends with my teammates. From basic circuit principles to breadboarding to soldering, I was excited to learn each new concept, and along with my teammates, put them into practice. This first experience in electrical engineering set the course for my academic and professional careers. I went on to study electrical engineering as an undergraduate and medical electronics and physics as a master's student. I currently design circuits and develop smart phone applications." *Degrees earned: B.S. in electrical engineering at Princeton M.S. in medical electronics and physics at Queen Mary University of London. Job title: Research Engineer, Georgia Tech Research Institute, Marshall Scholarship recipient.*

*Female Student, PGSS 2013 Project: "*For me, the Theremin project was particularly special…E&M concepts seemed pretty abstract… However, during the summer at PGSS, I got to watch all these come to life. It was exciting to me to apply all these theoretical concepts and watch a team work together to create a tangible working object. I was amazed how a diverse group of people, each with varying backgrounds in EE, could work so seamlessly together, helping each other out along the way. The project really solidified my passion for engineering. Currently, I am working on a joint project with NASA's Jet Propulsion Laboratory, designing and prototyping a landing mechanism for quadcopters for uneven and angled surfaces. Similar to the Theremin project, my team is composed of a variety of students of different grade levels and majors. It is exciting to see interdisciplinary teamwork come together." *Degree status: currently B.S. mechanical engineering, Caltech.*

*Female Student, PGSS 2013 Project: "*I came into the project with no prior experience with any type of electrical engineering... After five weeks, I could draw a circuit diagram, I had all the jargon down, and I had helped to construct a (nearly-functional) circuit - it's a real testament to how much the program teaches its students in so little time. What I really learned, though …was the importance of teamwork. When I came into Gov School - and I think this is probably true for a lot of other students - I was pretty independent in terms of academics. I tended not to trust other people with important tasks in group projects because I thought they wouldn't take them as seriously as I would… We all had goals and we all wanted nothing more than to accomplish them, but instead of competing with each other, we relied on each other - and that facilitated a kind of human connection that would never have been possible otherwise...it definitely impacted the way I work with other people and the way I view myself." *Degree status: currently B.S. chemistry major, Drexel University.*

Female Student, PGSS 2013 Project: "For me, the Theremin project confirmed my interest in electrical engineering. I had no prior experience of using breadboards, and it was really fun to be able to build such a complex circuit with the rest of the team…the project gave me valuable experience translating a circuit diagram into a physical circuit on a breadboard, and gave me practice debugging circuits, and soldering." *Degree Status: currently B.S. electrical engineering, marketing, and operations decisions in the Management & Technology Program, University of Pennsylvania.*

Only qualitative feedback from program alumni was available for analysis. Since the project has spanned two decades, it was difficult to find enough of the participants for a meaningful quantitative survey of the learning outcomes achieved. The student feedback showed all of the respondents continued on to get engineering or science degrees, and they all had extremely positive comments about their Theremin project. These professionals have the proper education and context to review this project with hindsight and assess its impact on a formative time in their academic careers. The common theme from all of the responses was that the students benefitted immensely from working on a team project with a high performing team of peers. The effective division of labor during the collaborative research project was new to many who preferred working as an individual or often would carry the team. Showing them the capabilities of a well-functioning team gave them an understanding and appreciation for teamwork they have used throughout their academic and career pursuits.

Many of the students also mentioned their amazement at their learning curve, beginning with little knowledge in a subject and they quickly assimilated the concepts needed to design and build a system. By compartmentalizing the project into subsystems and having small groups responsible for each subsystem, the students effectively learned how to build complex systems by breaking them down into manageable segments and then integrating and debugging the resulting pieces. Many cite this as their first experience taking theory and concepts from physics and applying them to a tangible result, and that inspired them to become engineers. Students have also reported building their own Theremins after the program, as part of a graduation project or just for fun.

The final presentations at the PGSS research symposium required that all team members speak in front of their peers and public. The understanding of the project by the entire team was evident to the audience. The journal papers also document the success of the teams and their collective understanding. The construction of a working Theremin in five weeks requires a team effort, and each person makes a significant contribution. The student feedback confirms the effectiveness of the project to teach engineering principles and inspire them to follow engineering career paths.

Conclusion

The Theremin has been demonstrated to be a flexible project to introduce students of all experience levels to learn the basics of electronics and circuit building at the high school level. With modest supervision and assistance, students are capable of constructing and debugging complex circuits, which is evident by the perennial success of these projects. By breaking down the Theremin design into subsystems, small groups can be given specific tasks in parallel which integrate for the final product, emulating a professional team development process. Aspects of aesthetics and ergonomics can be included with the packaging of the device to take the project from design to functional prototype. Advanced students can be given the option of proposing and creating design modifications to the standard Theremin such as additional pitch antennae, synthesizer type effects, other music making attachments, etc. The creation of a musical instrument is an enticing project that had on average equal gender participation, when students could freely choose their summer research project. Students who participated in the Theremin project cite it as a major factor in guiding their college and career interests and was their first impactful introduction to interdisciplinary teamwork and application of electronics theory. The finished project also generates a showpiece that can be put on display or demonstrated to excite others about studying electronics.

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