MAKER: A Sound Introduction to Engineering Technology and Product Development

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Abstract

This paper outlines the implementation of an active-learning experience that has been designed to introduce high school students to engineering technology and product development. In a three-hour program, students are guided through the construction of an amplifier circuit and speaker cone assembly while the various engineering roles with product development are discussed. This multidisciplinary project touches on electrical, mechanical, and manufacturing roles in the development of a product.

The project begins with an introduction to the principles of soundwaves and amplification. Electronic design of the speaker includes discussion of component selection, explaining the need for each element of the design. Throughout the discussion, students are guided though the assembly process which involves soldering electronic components to a prefabricated printed circuit board (PCB), winding wire around a 3D printed bobbin, and fastening the components to a wooden base. Upon completion of the assembly, students are able to play music from their phones and electronic devices through the amplified speaker assembly.

This speaker project has been utilized through multiple sessions of Women in Engineering (WIE) summer camps involving high school female students. Surveys of students following the exercise indicate a high level of satisfaction with both the end product and the insights gained into engineering roles. Students walk away with a self-made product, and more importantly, a lasting impression of the accessibility of product development and engineering.

Introduction

Active learning with tangible examples has been shown to improve retention while increasing satisfaction with the learning experience[1, 3, 6]. Hands on activities which help high school students better understand engineering roles have also proven to be good recruitment tools.[2,9] In this project, a speaker-amplifier assembly has been developed to provide high school and even undergraduate students with a high impact active learning experience. The project emphasizes the various roles of engineering disciplines required throughout the product development process. The design of the speaker-amplifier allows for a multi-disciplinary approach to this process and can be completed in approximately three hours, making the project perfect for a half day workshop. Students are exposed to the physics of sound, electrical circuit design, mechanical design, and manufacturing considerations. This project was built off of prior success with a similar, but simpler, project involving the construction of an LED flashlight in one hour.[2]

Throughout the experience, a multidisciplinary approach is used to guide students through the assembly process. Construction begins with the base subassembly. Discussion revolves around product architecture and the importance of waiting until late in the assembly process to introduce product family variations. Next, the speaker cone and housing structure are assembled. This allows for discussion of mechanical design considerations such as geometry, structure, materials and manufacturing processes. This is followed by the circuit board assembly which involves soldering a variety of components onto a bare circuit board. This allows students to develop soldering skills as they begin with simpler components and progress to more difficult components with tightly spaced leads. This also allows for a discussion of circuit design and component functions as components are added to the board. Finally, after seemingly hours of tedious assembly steps, the three sub-assemblies all come together, culminating with a functional speaker. Students eagerly connect their phones to the speaker and smile with delight as they listen to the output of their efforts (Figure 1).

Students are fully engaged as learners, makers, and customers as each constructs her own speaker-amplifier. Student surveys following the exercise indicate satisfaction with both the learning experience and the final product. Students walk away with a self-made product and more importantly, a lasting impression of the accessibility of product development and engineering professions.

Figure 1. Final Speaker Product

Construction

The components of each speaker are pre-packaged into a kit for each student prior to the outreach workshop. The bill of materials for the speaker kit is shown in Table 1 and a list of assembly tools & equipment is shown in Table 2. As shown in the BOM, the total cost of the kit is less than $10 when purchased in quantities of 100 or more. Most of the components are standard catalog items with the exception of the Wood Base (Item 1), the Speaker Cone card stock template (Item 7), the 3D printed Speaker Frame (Item 8), and the Printed Circuit Board

(Item 10). These custom components have been developed by University of Dayton Engineering Technology faculty specifically for this outreach project. While these components may limit the ability to easily replicate the project, this level of refinement was carried out to improve both the final product and the overall student experience. These components can also be easily ordered or re-created directly from the electronic data files. The construction of the speaker is detailed in the steps that follow. It is very beneficial for students to work in pairs throughout the assembly process. Not only is it helpful to occasionally have an extra set of hands, but students will often learn from each other and help each other catch assembly errors along the way.

Table 1. Speaker Kit Bill of Material

Item	Description	Supplier	Part Number	Quantity	Unit Cost (100 qty)	Extended Cost
1	Base, Wood	1/2" Sanded Plywood (Hand cut 4" x 4")	Home Depot, Lowes, etc.	1	$ 0.15	$ 0.15
2	Flat Head Wood Screw, #6 x 3/8"	McMaster Carr	90031A146 (100 qty)	1	$ 0.04	$ 0.04
3	Battery Clip, 9V	Digikey	36-80-ND	1	$ 0.34	$ 0.34
4	Round Head Wood Screw, #8 x 3/8"	McMaster Carr	90190A146 (100 qty)	2	$ 0.02	$ 0.05
5	Neodymium Magnet .375D x .375L	McMaster Carr	5862K965 (10 qty)	1	$ 0.69	$ 0.69
6	O-ring, Buna-N, #110	McMaster Carr	9452K22 (100 qty)	1	$ 0.02	$ 0.02
7	Speaker Cone (Pre-printed card-stock template)	Custom	NA	1	$ -	$ -
8	Speaker Frame (3D printed from custom .stl file)	Custom	NA	1	$ 0.50	$ 0.50
9	32 Gage Magnet Wire (48 ft)	McMaster Carr	7588K89 (4350 ft)	0.011	$ 34.38	$ 0.38
10	Printed Circuit Board (3.0" x 1.5" x .06")	Custom	NA	1	$ 1.50	$ 1.50
11	R1, Resistor (10 ohm)	Digikey	PPC10W-1CT-ND	1	$ 0.08	$ 0.08
12	R3, Resistor (1000 ohm)	Digikey	PPC1.0KW-1CT-ND	1	$ 0.08	$ 0.08
13	U1, IC Socket	Digikey	ED3044-5-ND	1	$ 0.10	$ 0.10
14	C1, Capacitor	Digikey	445-8497-ND	1	$ 0.21	$ 0.21
15	LED1, LED Power Indicator	Digikey	754-1273-ND	1	$ 0.15	$ 0.15
16	SPEAKER, Connector	Digikey	ED10561-ND	1	$ 0.42	$ 0.42
17	C2, Capacitor	Digikey	565-4052-ND	1	$ 0.22	$ 0.22
18	SW1, Power Switch	Digikey	CKN10397-ND	1	$ 0.41	$ 0.41
19	Battery Cable, 9V, 6" leads	Digikey	36-236-ND	1	$ 0.39	$ 0.39
20	Wire Tie, 4"	Digikey	1436-1517-ND	2	$ 0.01	$ 0.03
21	INPUT Audio Cable with 3.5mm Plug	Digikey	1175-1449-ND (cut in half and strip ends)	0.5	$ 1.60	$ 0.80
22	R2, Variable Resistor Volume Control	Digikey	987-1277-ND	1	$ 0.51	$ 0.51
23	U1, Integrated Circuit Amplifier	Digikey	296-44414-5-ND	1	$ 0.68	$ 0.68
24	Flat Head Wood Screw, #8 x 2"	McMaster Carr	91070A205 (100 qty)	2	$ 0.10	$ 0.20
25	9 Volt Battery (not shown)	various	-	1	$ 1.00	$ 1.00
					Total:	**$ 8.95**

Table 2. Assembly Tools & Equipment

Hot glue gun & hot glue sticks	Side Cutters
Scissors	Wire Strippers
#2 Phillips screw driver	Awl or punch for marking screw holes
Jewelers flat head screw driver	Sand paper
Soldering iron & solder	

Construction begins with the Base Assembly (Figure 2). The Wood Base (Item 1) can either be pre-drilled with screw hole locations, or a printed template can be used in combination with an awl or punch to mark the screw hole locations during the assembly process. Once the Wood Base is prepared, the #6 x 3/8" flat head screw (Item 2) can be driven in flush with surface of the base. The Battery Clip (Item 3) is assembled with two round head screws (Item 4) to retain the outside edges of the clip. Finally, the Magnet (Item 5) attaches to the flat head screw and an O-ring (Item 6) is placed around the magnet.

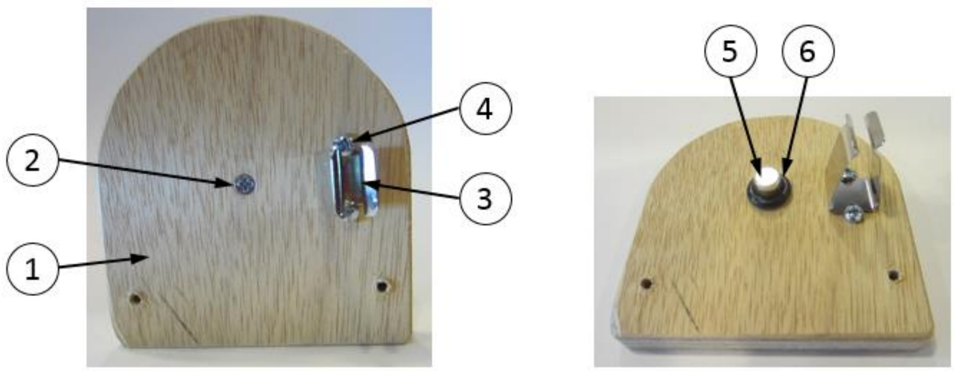

Figure 2. Base Assembly

Next comes the Speaker Cone and Frame Assembly (Figure 3). Winding the magnet wire is a tedious process, but it does provide time for discussion and opportunity to engage students in the manufacturing process. It is also extremely beneficial for students to work in pairs for this step. 48 feet of 32 gage magnet wire (Item 9) should be pre-measured for each kit, or an appropriate method should be provided for students to accurately measure the wire during assembly. About 6 inches of loose wire should be left exposed for future connection to the circuit board. This wire can be gripped against the side of the 3D printed speaker frame (Item 8) as the bulk of the wire is wound around the bobbin portion (narrow diameter) of the frame. Care should be taken to keep the wire taut and evenly distributed across the bobbin while winding. Upon completion of the winding process, about 6 inches of loose wire should once again be left for future connection to the circuit board. A narrow bead of hot glue can be placed across the length of the wire coil to keep it from unraveling. An additional bead of glue can be used to secure the two 6 inch loose ends to the flat underside of the speaker frame. In preparation for connection to the amplifier circuit, the clear insulating coating should be sanded or scraped from the last half inch of each lead. The wire will appear slightly shinier once the coating is effectively removed.

With the coil in place, attention can now be turned to the Speaker Cone (Item 7). The speaker cone must be cut out of a pre-printed card stock template. A single radial slit is cut into the disk so that it can be formed into a cone. A bead of hot glue along the overlap at the radial slit will secure the shape of the cone. Finally, the cone can be attached to the top of the speaker frame by placing a bead of hot glue around the circumference of the large open hole above the wire bobbin. This completes the Speaker Cone Assembly.

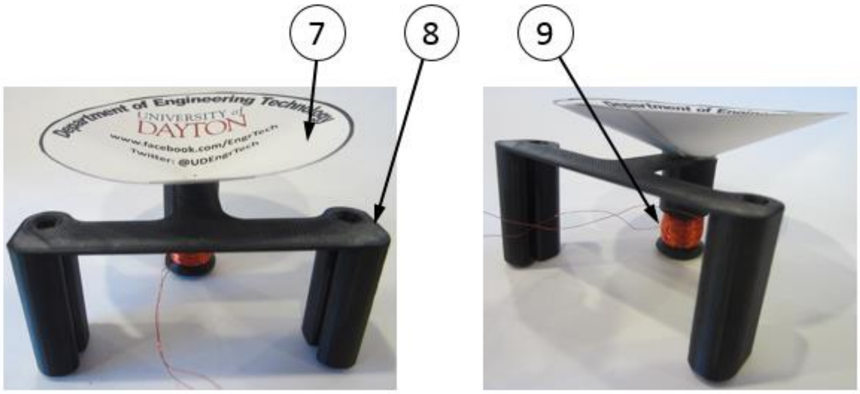

Figure 3. Speaker Cone and Frame Assembly

The Amplifier Circuit Board (PCB) Assembly (Figure 4) comes next and will account for the majority of the speaker's assembly time. Again, at this time it is very beneficial for students to work in pairs for assistance in manual tasks and help with trouble shooting. Components are generally soldered to the PCB in order from smallest-to-largest for improved accessibility during the assembly process. While it is not required, the components are typically soldered to the PCB in order of each Item number (11 thru 23). Most components can be inserted on the front of the board and soldered on the back side of the board. Excess leads can be trimmed on the back of the board as appropriate. Any specific tips or instructions follow below in order of component assembly.

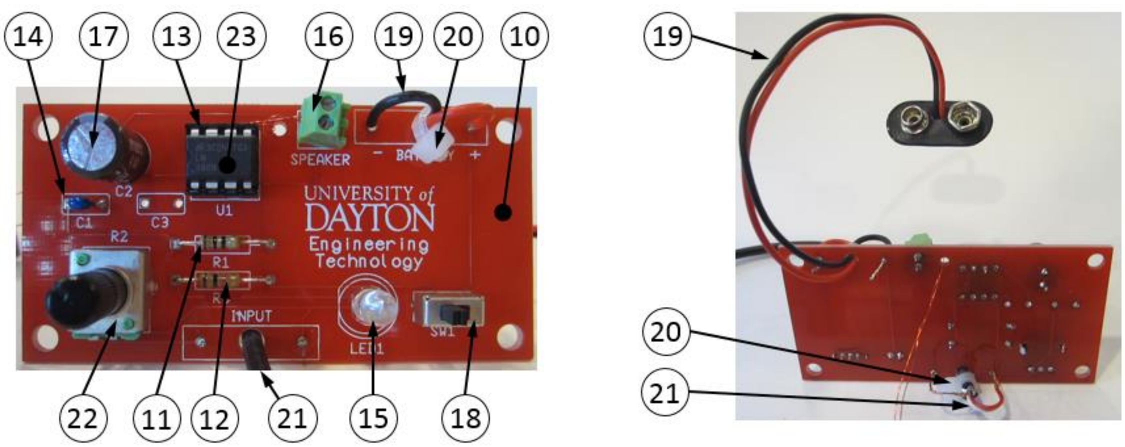

Figure 4. Amplifier Circuit Board Assembly

Items 11 & 12 (R1 & R3 Resistors): These resistors look very similar, but are not interchangeable. If they are not installed correctly, the power indicator LED will be very dimly lit with power applied and damage can result to the circuit assembly. The R1 resistor is 10 ohms and should have two black bands in the middle. The R3 resistor is 1000 ohms and has a black and red band in the middle.

Item 13 (U1 Integrated Circuit): Only the socket should be initially assembled to avoid applying any heat to the actual IC chip (Item 23). Polarity is important so the socket must line up with the outline on the PCB.

Item 15 (LED1 Power Indicator): Polarity is once again important in this step. The flat edge of the LED should be oriented with the flat portion of the outline on the PCB.

Item 16 (Speaker Connector): The connector should be oriented such that the speaker wires can enter from the central hole in the PCB.

Item 19 (Battery Cable): The cable should be fed through the hole between the battery +/- connections from the back of the PCB. Polarity is important. The red lead should be inserted back through the positive (+) PCB hole. The black lead should be inserted through the negative (-) hole. The leads should then be soldered and trimmed from the back side of the board. A wire tie (Item 20) should then be used to tie the red and black wires together on the front side of the board as shown in Figure 4. This provides a strain relief for the cable and protects the solder connections to the PCB.

Item 21 (INPUT Audio Cable with 3.5mm Plug): This cable is purchased as a single cable with a male plug on each end. The cable must first be cut in half, insulation removed from the first two inches of cable, and insulation stripped about half an inch back on the red and white wires. This preparation can be done prior to the workshop if time is limited or it can be used as an active learning experience during the workshop. Once the cable is prepared, it is assembled much like the Battery Cable. The cable is first pushed through the central hole on the front of the board. The red and white leads are twisted together and fed back through one of the INPUT holes. The bare copper lead should be fed back through the remaining INPUT hole. The leads can then be soldered and trimmed from the front of the PCB. Finally, a wire tie should again be added as a strain relief on the back side of the PCB as shown in Figure 4.

Before moving on to the final speaker assembly, it is a good idea to verify that the power indicator LED (Item 15) lights up when power is applied to the circuit. This can be accomplished by attaching the 9 volt battery to the battery cable. If the LED does not light up immediately, flip the switch (Item 18) to the opposite position. IF the LED will not light up or is very dim with the switch in either position, further trouble shooting of the circuit assembly may be necessary. If the LED lights up, the amplifier circuit assembly is complete and is ready for final speaker assembly.

The final speaker assembly steps illustrated in Figure 5. The Amplifier PCB (Figure 5C) assembly slides into the grooves of the speaker frame (Figure 5B). The most difficult task in this assembly is connecting the speaker wires to the amplifier. The speaker wires route through the top central hole next to the green connector. The two speaker wire ends, which had been previously stripped of any insulating coating during the speaker cone assembly, should now be carefully inserted into the two respective receptacles on the green connector. This may require the use of tweezers to hold each wire in place while the corresponding clamping screw is tightened with a jeweler's flat blade screw driver. Once this step is complete, the two remaining screws (Item 24) can be used to attach the speaker & amplifier assembly to the base assembly (Figure 5A). The speaker coil should slide over the top of the neodymium magnet on the base. Finally, the 9 Volt battery can be re-attached and slid snapped into the battery clip behind the amplifier.

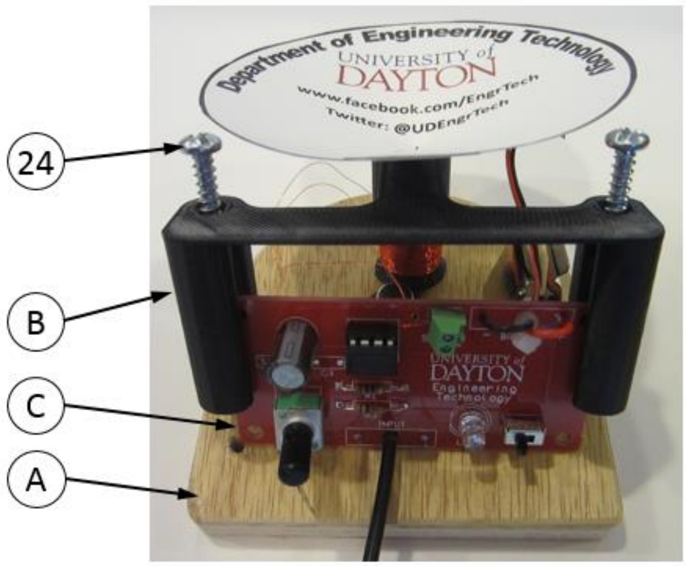

Figure 5. Final Assembly

The final assembly should be ready to connect and play some music as shown in Figure 1. Additional pictures are provided from all sides of the final product in Figure 6 for further clarification of the intended final assembly.

Method of Instruction

As students are guided through the construction of the speaker, they are also instructed on the theory of operation and practical engineering considerations pertinent to each step. Instruction begins with a basic explanation of the physics of sound. This involves a discussion of sound pressure waves, vibrations, pitch, volume, and amplification. These concepts are then related back to the workings of a speaker. Depending on time constraints, many questions can be explored as appropriate: *Where does the sound pressure wave originate? (the speaker cone); What drives the speaker cone? (vibrations generated from an oscillating magnetic field); Where does the electrical signal come from to drive magnetic field? (an audio source); How can we increase the volume of the sound? (an amplifier).*

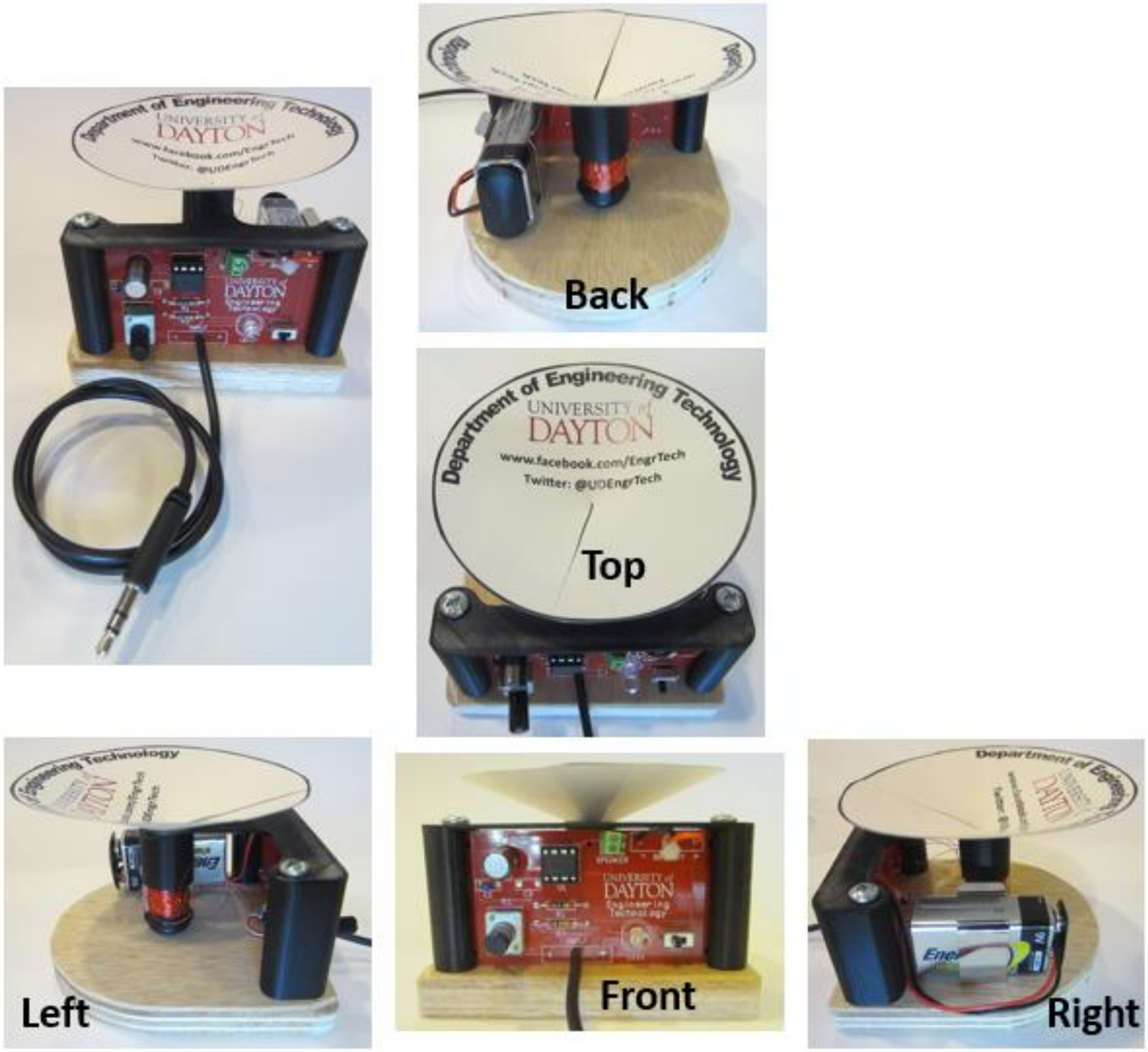

Figure 6. Views of Completed Assembly

This discussion should lead into the specific sub-assemblies that the students will begin building so that they can eventually put them all together to form a complete speaker/amplifier system. The assembly of the speaker base / chassis lends itself to a discussion of various manufacturing and assembly considerations. First, while marking the holes on the base with the paper template and awl, one can discuss the use of jigs & fixtures in manufacturing to increase quality and reduce manufacturing time. Another discussion could focus on assembling products around a common chassis. Many product families often share a common chassis to maintain a generic product line that can be customized with higher end features in the final steps of assembly or even further downstream.

The speaker cone and frame assembly provide an excellent opportunity to discuss mechanical design considerations. The mechanical design process entails considerations of geometry, materials, and forces. This often begins with concept sketches and eventually leads to solid models that provide a virtual prototype of a product's geometry as illustrated in Figure 8. In addition, computer analysis tools such as Finite Element Analysis (FEA) can be used to evaluate forces and, in this case, potential issues with resonant frequency mode shapes (Figure 9). Once the virtual prototypes have been proven out, Engineers can create physical prototypes using technologies such as 3D printing. Whereas many products are designed for final production with other processes, this speaker frame has been specifically designed following rules to optimize the part for 3D printing as the end manufacturing process.[8] This has enabled the part to be successfully printed without support material on each of the consumer grade Fused Filament printers shown in Figure 10. Printing on a consumer grade printers allows the component to be printed for less than 50 cents in material. Design skills for additive manufacturing are becoming increasingly important for mechanical and manufacturing engineering graduates.

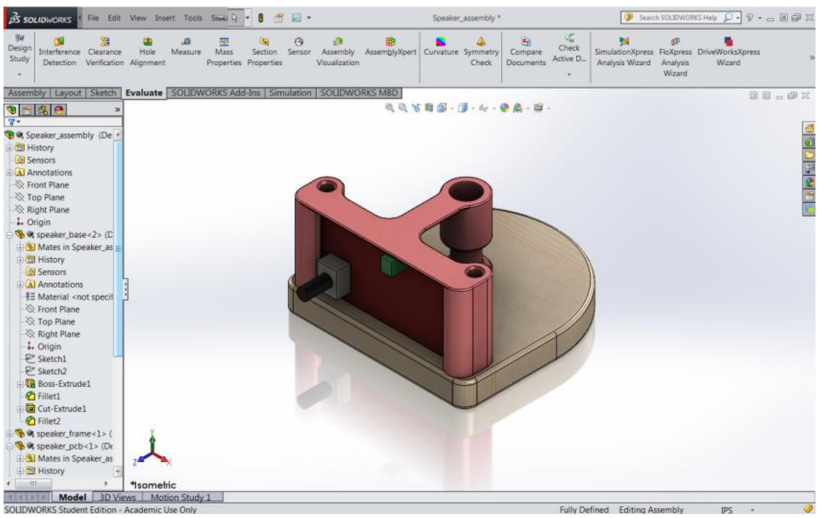

Figure 8. Solid Model of the Major Speaker Components.

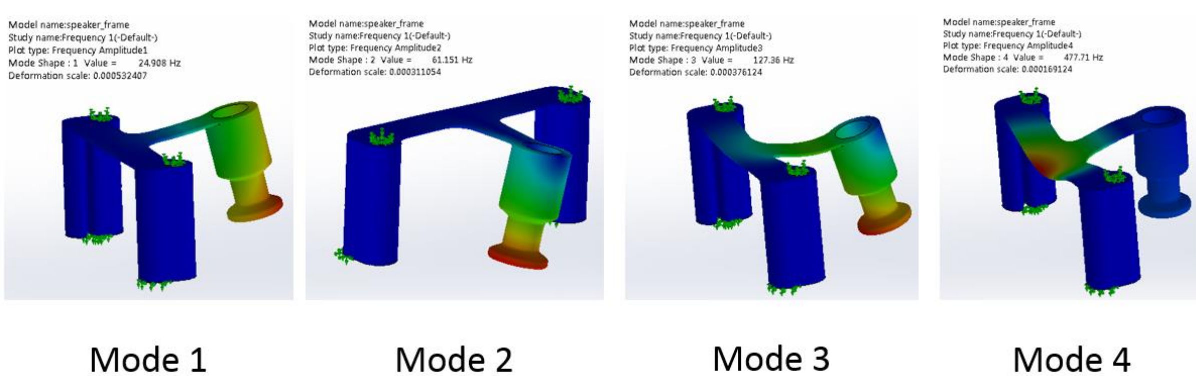

Figure 9. Finite Element Analysis of Resonant Frequency Mode Shapes.

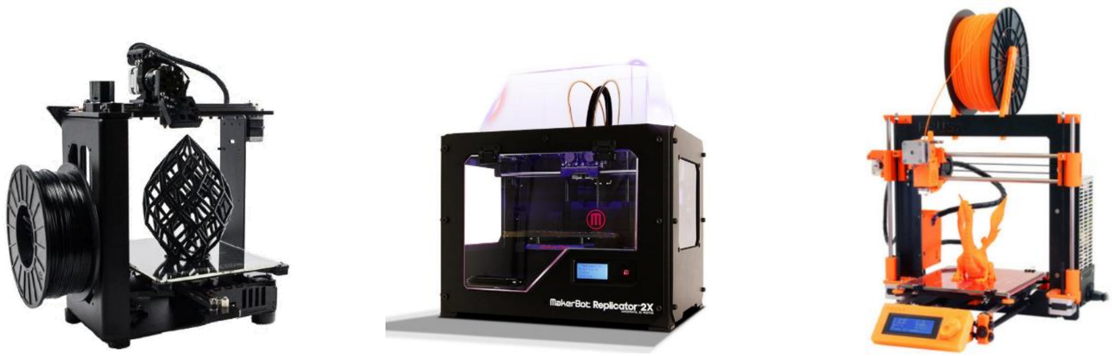

Figure 10. Consumer Grade 3D Printers.[4, 5, 7]
A. MakerGear M2; B. MakerBot Replicator 2.X; C. Prusa i3 MK2

Winding the magnet wire around the speaker bobbin also provides time to discuss the value of automation for tedious repetitive processes like these. Machines are typically used to do these tasks for components such as motor windings, transformers, speakers, and electromagnets. Automation of our bobbin winding exercise would greatly impact speed, precision, quality, and cost.

Assembly of the amplifier circuit board provides the opportunity to introduce the role of electrical engineering in product design & development. Similar to mechanical design, the circuit begins as a concept. Electrical circuits can also be prototyped with computer analysis tools. From this step, a circuit is often prototyped using bread boards and jumper wires to connect components and test out the physical circuit. Finally, once the concept has been proven out, Electrical Engineers can move towards a custom Printed Circuit Board by laying out traces and components with ECAD tools. Manufacturers can use these files directly to generate the customer printed circuit boards like the one used for this project.

In addition to the design process, many of the students will have the opportunity to develop a new skillset as they learn to solder for the first time. As time permits, the role of specific electrical components can also be discussed as they are soldered in place on the circuit board. Resistors, LED's, batteries, switches, integrated circuits, and other components all offer additional opportunities for learning and discussion.

As the final assembly comes together, it is a good time to touch on the role of the customer in the product development process. Most of the students will agree that they are extremely satisfied with their product. This is important because this speaker and the entire experience has been designed with them in mind as the customer. Some possible questions for thought include: *Why then might another consumer be disappointed if they were to buy one of our speakers? Also, why are there literally thousands of speakers on the market today to satisfy the single customer need to produce sound from their electronic devices?* Of course the answers may seem obvious, but it highlights the importance of considering specific customer needs first and foremost in the product development process.

Conclusion

While assessment of this specific workshop is not conducted separately, participant surveys are conducted for the Women in Engineering (WIE) Summer Camp as a whole. This camp included additional workshops that also provided insight into other engineering disciplines. Data from the 2016 summer camp survey revealed that 35 of 36 participants felt the camp was influential in regards to choosing a plan of study for college. These results are especially encouraging coming from young women who are faced with pivotal decisions in choosing a career path that has typically been dominated by males. In addition to the Likert type survey questions, students were also given the opportunity to express general comments about their camp experiences. A few of these comments are included below, again illustrating the positive impact of both the workshop and the overall camp.

- "It taught me about the opportunities available in engineering. I learned what I want for my future and this camp gave me a confidence in what I want to do with my future…"
- "I believe the women in engineering is valuable because it seriously helped me see the broadness of engineering, and I learned about fields that I never thought either existed or thought engineering would be applied to it."
- "It allowed me to see what engineers actually do in the real world. The field of engineering is so broad that I had no idea what those jobs would entail. This camp helped me decide if I want to consider engineering as a possible career path."
- "It shows young girls the various opportunities available to them in the engineering industry. It shows them that there is more to it than just STEM."

As mentioned earlier, the participants of this workshop walk away with a sense of pride in making their own speakers, but more importantly they gain a sense of the accessibility of product development and engineering as a career choice. The speaker design, assembly, and instructional methods have been developed to encompass a broad range of engineering disciplines while fitting within the time constraints of the workshop. This has allowed the workshop to maintain a hands-on experience while also emphasizing the broader impact of engineers in product development.

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