Young Makers in the First-Year Engineering Classroom: Educational Pathways, Implementations and Implications

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Abstract - **The rising popularity of the maker movement may increase the numbers of students interested in, and majoring in, engineering. For first year engineering students, engaging with the maker community and campus makerspaces could also serve to help form a basis for the broader student learning outcomes needed to succeed in engineering majors and careers, especially as identified by ABET. Our work investigates what engineering students learn from their educational pathways and engagement with making about (awareness) and during (context) the beginning of their engineering studies. We will share an operational framework of the attributes of making and how those can be supported with messaging about engineering programs and introductory projects. We have interviewed 36 young makers (ages 7-17) and 40 adult makers about the creations they brought to flagship Maker Faires to better understand what engineering skills makers are learning. From qualitative artifact elicitation interviews it can be shown that makers are gaining experience in a variety of ABET a-k (Student Outcomes) applicable experiences. Over three-quarters are learning effective communication skills (g), over half display traits associated with successful lifelong learning (i), and a third are identifying and solving engineering problems through system design with realistic constraints (a, c, e). Makers are exposed to a variety of types of engineering, half of our interviewees engaged in hardware and software design, half learned physical fabrication methods, and one-quarter learned CAD modeling. Finally, half of the young makers we interviewed are interested in pursuing engineering degrees. Makers learn broadly applicable engineering skills, a love of learning, and how to rapidly turn their ideas into physical artifacts. Courses introducing engineers to a maker mindset could introduce early engineering concepts across a variety of specialties, achieve ABET Student Outcomes, and instill life-long learning skills to aid their education.**

Index Terms –ABET, Maker Mindset, Making, Student Outcomes

INTRODUCTION

There is an influx of interest in making and an ever-growing community of makers interested in engineering at the undergraduate level. To better understand how making can be used a learning tool for pre-engineering students, university students, and adults, we must first understand what skills, specifically, makers are learning. We interviewed 76 makers to discuss artifacts they had created for presentation at flagship Maker Faires. Makers, both young and adult alike, learn a variety of skills and knowledge to create technically sophisticated artifacts of personal interest in their informal making activities. Skills makers identified as learning are categorized according to their fit with ABET standards for selected engineering, engineering technology, and computing programs. By finding the specific areas of intersection between the skills used in making and the skills associated with ABET student learning outcomes a-k, and program criteria, we can better understand what skills young makers may be entering college with as well as what engineering skills more broadly can be successfully taught through self-guided, project-based learning.

In this research paper, the skills makers are learning are categorized according to their fit with current (as of July 2016) ABET standards. Makers, both young and adult alike, learn a variety of skills and knowledge to create technically sophisticated artifacts of personal interest in their informal making activities. Here we argue that making (open-ended, student-led project based learning) and the maker mindset (failure-positive, collaborative, playful) can provide a useful template for teaching some skills and attitudes relevant to ABET outcomes for engineering students. This paper demonstrates that ¾ of interviewed makers are learning how to communicate technical details to a wider audience, ½ are learning valuable techniques to foster lifelong learning, ½ are learning how to apply engineering knowledge to solve problems, ½ are learning specific skills applicable to electrical engineering and manufacturing engineering programs, ⅓ are working on multidisciplinary teams, and ⅓ are designing systems with realistic constraints. Each of the above categories is part of ABET's accreditation process for engineering programs. Communications skills, the ability to engage in self-directed learning, and the ability to function in a real world work environment (teams and constraints) are recognized to be areas in which traditional engineering training is lagging [1]. Making offers a potential lens to highlight those areas which may be lagging in a more traditional engineering education. Furthermore, as part of ABET accreditation criteria, universities are asked to demonstrate continuous improvement. For many this means opening makerspaces and bringing project-based learning pedagogies and hands-on laboratory experiences to their undergraduate engineering programs. There is a tension rooted in ABET accreditation standards for what is expected to be taught in computing and engineering undergraduate programs, how to assess and what values about our enterprise of engineering education.

This study used ABET criteria as a framework for a thematic analysis of artifact elicitation interviews conducted with young and adult makers about the skills they used to create artifacts displayed at Maker Faires. A total of 36 self-identified young makers, age 12-17, and 40 adult makers, age 18-60+, were sampled purposefully and stratified by experience (through their formal education, informal engineering education, and tinkering activities) and membership in an underrepresented group based on ethnicity and gender. Their interviews were then coded with ABET student learning outcomes a-k plus and additional program-specific criteria.

The maker movement is an emerging and developing sub-culture that values the tinkering, hacking, re-making, and creating of technical artifacts. Makers are rich in creative confidence, with expertise in the ability to learn new skills as needed rather than already possessing immediate solutions to the problems that they encounter [2]. Creative confidence, in terms of making, can be summed up as a failure positive mode of learning where the creator trusts in their own ability to solve problems and celebrates learning through iterations and failure [3]. This confidence comes from an understanding that problems have many solutions, and through practical experience, one can learn those solutions. Making comes from an imaginative, creative mind-space, and is often done outside the confines of established engineering education curricular activities [4]. Making has a do-it-yourself ethos and is historically rooted in efforts like *Popular Mechanics* magazine who demystified everyday stuff for hobbyists and the *Whole Earth Catalog: Access to Tools* [5] who surveyed everyday tools for the counterculture movement of the 1960s. Additional real-world touchstones are the growth of Radio Shack stores and the 1980s television program *MacGyver* where the lead character would resolve each episode's predicament by fashioning an escape plan out of found objects [6]. Technology and sharing of information via the Internet has greatly increased the ability for smaller communities with shared interests to coalesce and grow.

WHAT IS A MAKER

The label "maker" is a self-determined one assigned by affinity to or involvement in a larger maker community. Both our participants as well as the founder of MAKE Magazine, Dale Dougherty, would suggest that all people can be makers, with self-identification as a maker and the desire to tinker being the only real criteria [7]. Makers are do-it-yourself-minded individuals participating in informal communities (doing-it-with-others) that support and celebrate building and prototyping technical proof-of-concept exploration and ad-hoc product development. A maker is a modern-day tinkerer and hands-on doer and fashioner of stuff. The range of expertise could be large but novices and experts alike share an enthusiasm and appreciation for building and creation. Individuals and groups embark on projects of all sorts, led primarily by their interests and curiosities, informed by their skills or the skills they want to learn. For example, one might make creative efforts like fire-breathing robots as performance art, combining contributions from community members with electrical, mechanical and embedded systems know-how. Makers exemplify the collaborative model of *additive innovation* by seeking and offering inspiration in their community, sharing and learning recipes with others, iterating on their own designs, and sharing artifacts of their designs back with the community to inspire others [8].

Makers participate in communities of practice, [9] gathering with like-minded individuals and groups to learn skills and share interests and affinities. They populate makerspaces and hacker spaces [10] and use commercial ventures like TechShop [11] to gather with other makers. A significant part of such participation is to benefit from opportunities to continue learn from, teach and mentor other makers.

THE MAKER MINDSET

In the context of this paper, the maker mindset is considered the attitude that makers use in their problem solving process. The primary components of this mindset are a creative confidence, collaborative sharing of knowledge between makers and a sense of playfulness that drives project decisions and guides the learning process [12]. Additionally, making is approached with a growth-mindset where individuals strongly hold the belief that knowledge and skills can be acquired by anyone with the motivation to learn [13]. These approaches to problem solving can be best summarized in the words of our interviewees.

Any problem you're approaching, it doesn't matter if you're problem is to design a dowel connector or that one person on your team who you really can't work with, you are going to apply the same skills in making. Try something, maybe it won't work, you can try again. The world does not end if you're initial design rolls off the table when you connect it to a dowel. The world does not end if your initial design has holes that are the wrong size. The world does not *end if you're initial design is not big enough. You can move on and try again, everything is an iteration and throughout your whole life you're going to be varyingly running through iterations or tripping and flailing your way through your iterations, but you can always try something again and failure is part of your process, not the end, you're not done when something fails.*

– Emma 7th grade maker

The message I'm trying to get across is that the Arduino controller is an incredible versatile thing and it's great for fun and it's great for work. So I'm a scientist by day and I make costumes by night and it's really useful for both of them.

– Mia, Bioengineering Postdoc

The engagement with materials, design, building and making, has been long used by artists and designers to grow creativity as well as practical skill in creating. The Rhode Island School of Design, for example, engages its students in critical making to enhance their abilities as designers through hands on interaction and the creation of physical artifacts [14]. Likewise, for engineering educators, this mindset offers the potential to open up some engineering classes to be project based, student led, and evaluated on process and teamwork over final outcomes. While not all classes could benefit from these traits, valuable skills for communications, project design and analysis, and lifelong learning, as well as practical skill at building and interacting with the artifacts of engineering can be gained from classes structured in such a manner. These same skills are invaluable building blocks for beginning engineering students.

RESEARCH DESIGN

Under thematic analysis as a theoretical framework, this study used the tool of artifact elicitation interviews to collect the stories of young and adult makers about the skills they used to create artifacts displayed at Maker Faires. A total of 36 self-identified young makers, age 12-17, and 40 adult makers, age 18-60+, were interviewed. The interviewees include both adult makers as well as pre-college makers. Allowing for a clear view of adults post-college as well as those entering college in upcoming years. Participants engaged in approximately 15-minute interviews about the artifacts they created and displayed at two flagship Maker Faires: the Bay Area Maker Faire in San Mateo, CA and the World Maker Faire in Corona, NY. During the interviews, makers answered questions about where and how they learned the skills needed to build their creations, their attitudes towards learning, and their goals for the future. Their interviews were then coded (mapped using qualitative methods) with ABET student learning outcomes a-k and additional program-specific criteria. Coding was based on participant views of what they had learned to create their object as well as the interviewer's observation of their artifacts. To see our research design, demographics, theoretical framing, and results in more depth, and with additional detail on proposed ABET criteria, please see "How Can Makers Skills Fit in with Accreditation Demands for Undergraduate Engineering Programs", the authors' paper presented at ASEE 2016 on which this paper is based [15].

RESULTS AND ANALYSIS

This paper argues that young and adult makers are learning valuable engineering skills, both those represented by ABET Student Outcomes a-k, as well as program specific skills. The knowledge makers are acquiring is relevant to understanding how the growth of makerspaces in universities can be leveraged to meet existing and future accreditation standards and to guide course design for early stage engineering students. Below, the results are visualized and each section, Criteria 3 and Program Specific Skills. For reference, the raw results are shown below.

Table I
Raw Coding Results

ABET a-k	Sources	Percent
(a) Apply sci, eng, math knowledge	33	43%
(b) Design and conduct experiments	8	11%
(c) System design with constraints	29	38%
(d) Function on multidisciplinary teams	20	26%
(e) Identify and solve eng problems	22	29%
(f) Professional and ethical responsibility	12	16%
(g) Communicate effectively	60	79%
(h) Broad education	35	46%
(i) Lifelong learning	42	55%
(j) Contemporary issues	9	12%
(k) Use engineering tools	13	17%
Engineering Experience		
Is an engineer (adult)	14	35%
Wants to be an engineer (young)	18	50%
Program Specific Criteria		
Electrical and Computer Engineering	43	57%
Manufacturing Engineering	37	49%
Mechanical Engineering	21	28%
All - Science Fundamentals	20	26%
All - CAD Skills	18	24%
Computer Science Only	3	4%
Biomedical Engineering	3	4%
All - High Level Math Skills	2	3%
N = 76, 40 adult, 36 young, population = 1000		

In almost all of the above categories, young and adult makers showed similar percentages in their responses. Major deviations are detailed in the Figure 1 below. Unsurprisingly, adult makers have broader life experiences and use more rigorous experimental designs. Young makers appear to be more likely to use CAD programs in their designs than adults.

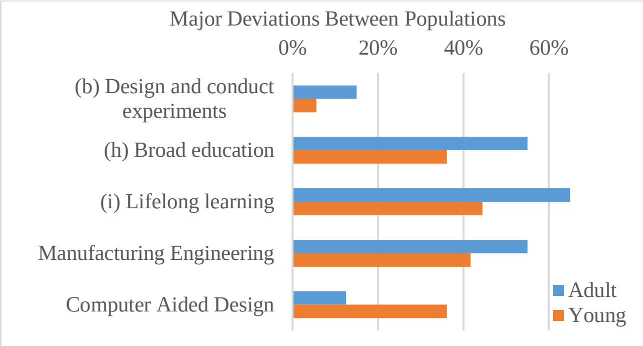

Figure 1
Deviations Between Populations

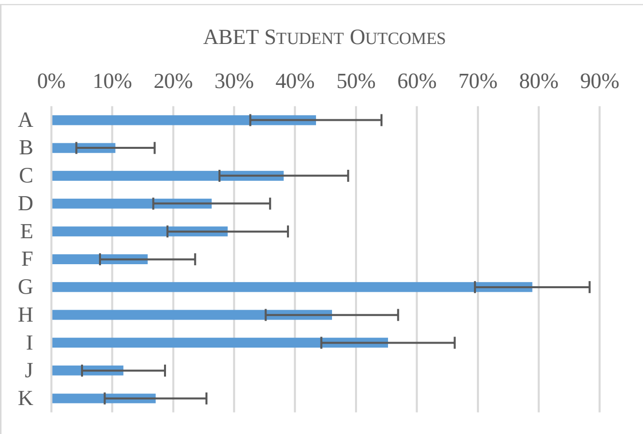

Figure 2
ABET Student Outcomes

In Figure *2*, (see Table I for a-k descriptions) we can see that the majority of makers exhibited effective communications skills. Almost 80% were able to clearly explain their technical project to a wider audience and/or mentioned specific cases where they effectively communicated in other situations. For example, one young maker designed a PowerPoint presentation and pitched an idea for a makerspace to his local school board. Another young maker produces a YouTube channel describing various science and engineering projects, has published a series of making books, and speaks regularly at Maker Faires on making and education. An example among adult makers is a group which communicate physics principles to an audience using a gigantic Rube Goldberg machine based on a children's game. Additional areas which makers are acquiring skills are lifelong learning, designing systems or projects within realistic constraints, and the application of science and engineering to solve problems. In the category of lifelong learning, most makers are highly adept at finding out how to solve problems by using internet searches, forming collaborative groups, and digging through existing literature to find solutions to help build their specific projects. The methods used by makers for finding project focused solutions are performed in a just-in-time fashion. When a project requires a solution, the maker finds out how to do it, applies the solution and moves on with the project. This ad-hoc method of contacting fellow makers, reviewing online sources, or forming groups to tackle a problem mirrors problem solving in a real world environment. If makers were imagined as employees in a technology firm rather than hobbyists, this ability to solve problems outside of the baseline knowledge acquired in university would be strongly valued. This willingness and drive to learn and expand their knowledge is an example of the maker mindset's focus on growth through experience.

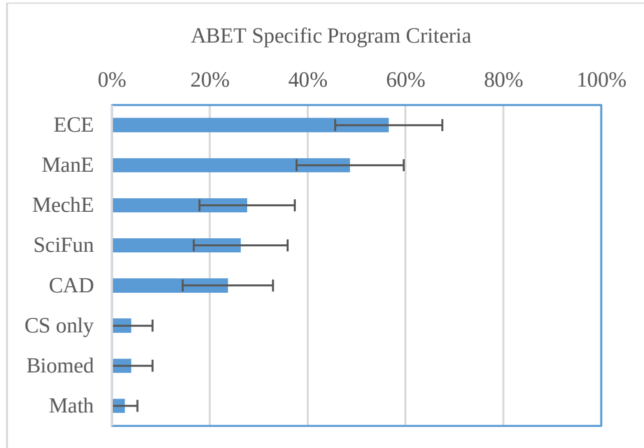

FIGURE 3
ABET SPECIFIC PROGRAM CRITERIA

In terms of program specific ABET criteria, it is clear that makers are primarily learning the skills associated with building systems with hardware and software components, such as robots, drones, interactive games, and with fabrication techniques. It is worth noting that an area makers are strongly lacking in terms of engineering education is higher math skills. While our data collection methods did not specifically ask interviewees if they used higher level math in the creation of their artifact, only one respondent mentioned using calculus and polar coordinates as a skill learned for their project. This suggests that to effectively use making as an educational tool, explicit mathematical elements may be needed during project creation or evaluation. Methods for doing so are further elaborated on in the discussion and conclusion sections of this paper.

In contrast to higher math, makers are learning a great deal about the integration of hardware and software components to form complex systems. Tony (pseudonym), a 14-year-old maker needed to identify and create a prototype solution for his final middle school project. He identified firefighting as a dangerous job which could be performed by robots. He then designed a prototype firefighting robot. This robot used a laptop running Linux to run pathing functions, which were then sent via WiFi to his foot-tall robot. The programs to drive the robot were written by him using Python and C. The robot itself was a combination of 3D printed and laser cut components with an Arduino board acting as the local brain for the robot. Mechanically, the robot used four two way wheels so it could navigate corners in a maze without turning. Finally, the robot had a fan attached which it would use to blow out a candle once it had been navigated to the "fire". Tony had analyzed his system and recognized weaknesses in his design; seeing what the robot saw on the laptop had a 30 second delay, stairs would be a problem for the robot, and a fan wouldn't work well on an actual fire. However, as a prototype, he considered it a successful starting point. To take his project to the next level, Tony recognized he would have to learn more about both programming and hardware. Two of our team's assistants, both juniors in electrical engineering, remarked on how this was a more impressive project than many of their classmates would create for a senior project. While Tony's artifact was particularly impressive, even for Maker Faire, and represented examples applicable to almost all of the a-k Student Outcomes and skills applicable to electrical engineering, it demonstrates how allowing a student to choose a problem they're passionate about, and then create a prototype solution can lead to an immense amount of learning.

It is worth noting that more than half of the makers interviewed built systems using software and hardware components, many used fabrication methods associated with mechanical and manufacturing engineering, and around ¼ of makers used CAD programs to design their artifact in 3D prior to creating it. This seems in no small part to be due to the increased accessibility of electronics and fabrication tools. Desktop 3D printers, laser cutters, and cheap, easy to program microcomputers such as Raspberry Pi and Arduino featured prominently in many artifacts. When taken as a whole, makers are learning to identify and solve problems they care about using technology.

With regards to pure computer science and biomedical engineering, it is either very uncommon for makers to engage exclusively in these categories or our sample size is insufficient to show a reliable estimate for what makers are learning in these areas.

Finally, the maker community is formed of many current engineers as well as future engineers. Thirty-five percent of our adult participants either had been trained as engineers or are currently working in an engineering field. Some of the participants identified making as the hobby that allowed them to renew their love of engineering or inspired them to learn additional engineering skills outside of their original area of training. For example, after retiring from an electrical engineering career, Matt learned 3D design and prototyping to create a Rube Goldberg style amusement park for plastic frogs. Ray on the other hand was trained as a mechanical engineer, but learned about fluids, programming, and web interfaces to create a web-based watering system for his garden. Furthermore, this large percentage of adult engineers in the making community provides a social mentorship network which young makers are able to tap. Fifty percent of young makers identified engineering or computer science specifically as their major of choice going forward into college. These pre-engineering makers will likely enter their programs with an expectation that project based learning will be part of their education.

IMPLEMENTATIONS AND IMPLICATIONS

Implementing making in the context of first year engineering experiences can come in several forms, both formal and informal. Formally, introductory engineering design courses can be taught with a focus on student led, project based learning. Several examples the authors have used are listed below.

- Giant Lawn Games – Prototyping using Arduino, simple sensors, cardboard, and wood
- Alien Centered Design – Students prototype solutions for transfer students from another world
- Open ended final paper topics based on individual student technology interests

Informally, first year students can be introduced to on campus makerspaces where community members (more advanced students, student workers, and faculty) hold ad-hoc or planned sessions on teaching prototyping skills, engage in individual projects, or simply hang out and socialize while building. This community can be further fostered by yearly campus Mini-Maker Faires. Engaging makerspaces with other student organizations and clubs can also foster feelings of community for first year students. The combination, for example, of a makerspace and an Anime club could result in students seeing engineering as not only a professionally useful skill, but also something they enjoy for hobby and social reasons. As our interviewee Mia suggests in her quote in the introduction, the tools of the maker movement serve not only a STEM role, but also to integrate into a person's own hobbies and passions.

In the case of formal courses, the primary challenge facing the instructor was the change of roles from provider of knowledge to facilitator of learning. By opening up the course to student created projects and student led topics the instructor is forced to often respond to questions with, "I'm not sure, let's figure out how to solve that together." Course constraints can serve to make this uncertainty more manageable. Situating a project within a context (such as designing adaptive devices for aliens) and providing broad requirements such as requiring a project to use sensors and motors empowers students to solve problems that they care about. Alternatively, a paper topic be based on technologies that directly influence society on a large scale can serve to help students focus and help instructors simplify their course.

The implications of how makers are learning engineering related skills shows that some of the challenging areas to teach in engineering, communication skills, engineering design within real world constraints, the development of lifelong learning skills, can be taught by enabling a maker mindset. Through the use of playful topic areas and allowing students to define the problems they care about solving, early engineering students learn valuable lifelong learning lessons.

CONCLUSION

Making, in the context of student led project based learning, is producing young people and adults who possess valid engineering skills which are applicable to ABET accreditation. The maker mindset, with its focus on celebrating failure, learning through hands-on iteration, and collaboration between makers could well be adopted in some engineering courses to instill many of the ABET Student Outcomes as well as skills applicable to program specific criteria for electrical, mechanical, and manufacturing engineering. Specifically, the ability of making as a form of project based learning to instill a high level of communications ability, strong collaboration skills, the ability for self-directed learning, and perseverance is valuable to traditional engineering programs.

Additionally, Maker Faires offer a possible way for engineering educators to harness the maker mindset for their students. In a student driven, project based course, a mini-Maker Faire, the equivalent perhaps of an art class's gallery final could lead to successfully accomplishing ABET Student Outcomes. While perhaps more time consuming than a multiple choice test, an instructor can clearly determine what skills were used in the creation of an artifact through a semi-structured interview with the student.

This is not to suggest that making takes the place of rigorous engineering training. As the data presented in this paper shows, there would be a clear need for the purposeful integration of higher level math into project based making. Making alone does not appear to teach the math skills needed for today's engineer. The integration of higher mathematics into making could come in the form of post-prototype write-ups. Engineering students could, as often occurs in professional product engineering settings, create and test rough prototypes of their ideas, then, once a working model is established, dig further into the design by creating mathematical models for the object in terms of durability, cost, efficiency, etc. Future research on how to best integrate the qualities of a maker mindset with traditional engineering courses remains to be done, but the benefits of doing so are compelling.

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