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HIGHER EDUCATION MAKERSPACES AND ENGINEERING EDUCATION

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ABSTRACT

While originating in non-academic settings, the “Maker Movement” has quickly made inroads within academia. More significant than the facility that may be referred to as a makerspace is the makerspace culture, including the community that forms around the physical facility and the activities (programs) of that community. This paper reviews the history of the maker-phenomenon, details the development of higher education makerspace cultures over the last five years, and explores the impact of makerspace cultures on mechanical engineering education. The makerspace culture at two higher education institutions is used to illustrate the effect on engineering education within each institution. The paper concludes with a review of common practices within the higher education makerspace ecosystem.

INTRODUCTION

A combination of developments has led to a proliferation of spaces where members of an otherwise unaffiliated community can gather to design, fabricate and construct digital and physical objects. Such locations are commonly referred to as “makerspaces,” so named as they are the physical location where individuals create (make) all varieties of physical and digital designs. These facilities house the design and fabrication tools (such as hand tools, electronic equipment and manufacturing systems) to manipulate raw material and produce new objects and systems. Over the last ten years, makerspaces have been created within communities, schools, and businesses.

The term “makerspace,” is not limited to the facility, but can also include the community of members who use the facility and the activities of the community. This is very similar to the word “university,” which at times can include the physical structure, faculty, students, staff, and programs. The term “makerspace culture” describes the characteristics of this particular group of people. Within this paper, the broader definition of “makerspace” will be used to include the facility, participants, and programs. The “makerspace culture” is presented as the fundamental differentiator of that specific attribute of the community, with that culture centered on creativity, collaboration, sharing, and a sense of self-sustainment.

This paper examines four components of higher education makerspaces. The history of the “maker movement” is reviewed to understand the origin of this activity and to identify the common practices within makerspace communities. The role of makerspaces within higher education is then explored, noting the broad contributions an active makerspace community can add to an academic program. Adopting a makerspace culture, derived from the historical activities of the maker movement, is fundamental to the success of a makerspace within an institution of higher education.

The impact of a thriving makerspace culture on engineering education in general, and mechanical engineering education in particular, is examined by reviewing programs at the United States Coast Guard Academy and at Yale University. These examples illustrate how the makerspace (facility, community, and programs) has not only improved design skills but also served as a catalyst to export the maker culture beyond each institution. This area is of particular significance, as this impact has yet to be fully detailed within higher education. Finally, common practices within makerspaces are presented as models for other institutions that have created or are planning to create higher education makerspaces.

HISTORY OF THE MAKER MOVEMENT, MAKERSPACES, AND THE MAKER CULTURE

Before examining issues surrounding higher education makerspaces, it is important to review the historical framework of this form of learning and creating. It is proposed that a historical review can highlight the most appropriate features within the maker-movement that can serve as a framework for adopting this learning style into higher education. Central to the maker-movement history has been the increased availability, affordability and access to digital design and manufacturing tools, including rapid prototyping equipment, which has fueled the creation of community-based organizations. The concept of community-based, open-ended problem solving has also been adapted by a number of industrial companies to stimulate innovation and provide new avenues for product development. These developments provide a rich portfolio of lessons learned and common practices for higher education makerspaces.

A number of authors trace the modern maker-movement and the proliferation of makerspaces to origins in Europe in association with the simultaneous development of open-source computer languages and increased interest in computer hacking associations (1,2,3,4,5,6). While these activities were individual in nature, the value of learning from others and the speed of joint discoveries promoted the use of physical spaces where people could gather to pursue such activities. The digital origins of these associations facilitated the development of mechanical and electronic hardware fabrication facilities with a similar focus on community-based discovery and shared resources.

Parallel developments led to the wide-spread growth of community-based makerspaces during the period 2000-2010 in the United States. One contributing factor was the creation of “Fab Labs” (fabrication laboratories) as sites where computer-controlled tools were used to manipulate materials. Interestingly, the creation of the first fab-lab in the U.S. was an offshoot of an MIT class (“How to make (almost) anything”), first taught in 1998, and the research from the creator of this class, Prof. Neil Gershenfeld. Prof. Gershenfeld, along with others, founded the MIT Center for Bits and Atoms in 2001 to further explore the creation of physical objects from digital representations. The Fab Lab concept was viewed as a method to provide basic fabrication capabilities at a low cost and with low barriers to access. Common Fab Lab equipment included 3D printers, CNC mills/lathes, printed circuit board milling/etching equipment, CNC cutting systems, and microprocessor/digital electronics equipment. In addition to the equipment, the Fab Lab also provided training using the concept of peer-to-peer training to leverage the personal fabrication skills of Fab Lab members.

At approximately the same time a similar concept was developed at the community level, with perhaps the most well-known space being “NYC Resistor” which was founded in 2005. This organization is succinctly described on its web site as “a hacker collective with a shared space located in downtown Brooklyn. We meet regularly to share knowledge, hack on projects together, and build community” (7). Limited to approximately 30 members, the organization provides basic design and manufacturing equipment for its members and hosts classes in topics such as electronics design, microprocessor coding, rapid prototyping using a laser cutter, and sensor technology. The organization also hosts an annual “Interactive Show” where designers display their creations to the public.

Accompanying these academic and community-based developments for making were rapid advancements in digital fabrication. These advancements produced a series of inexpensive, small-scale (compared to their industrial counterpart) machines for additive manufacturing (primarily 3D printing) and subtractive manufacturing (including CNC mills/lathes/routers and laser/water jet/plasma cutters) as well as the proliferation of low cost microprocessors designed for the self-learning community. Specifically regarding this last area, companies such as Parallax, Arduino, Pololu, Raspberry Pi, beaglebone, and others were created as companies that not only offered (often) open-source hardware and software products but also supported a user community to learn from and teach one another how to use these systems.

Another important development that fueled the makerspace-movement was the increased ease of access to information, including equipment/tool training, “how to tutorials” for fabricating and assembling systems, and supplies (such as motors, materials, sensors, electronic components, and fasteners, to name a few). This access to information was also accompanied by the creation of a magazine (*Make:*) devoted to this topic, with that publication later developing into a number of other entities that helped propel the makerspace concept. Fundamental to these developments was providing information, assistance, and community support to a diverse audience that included students/educators, artists, industrialists, engineers, hobbyists, and others. Similar to the physical spaces, the on-line services were intended to not only provide information, but also serve as a social and collaborative network.

Collectively this series of developments has made the concept of makerspaces common in many urban and other densely populated areas. Community-based makerspaces have been created with missions similar to that of NYC Resistor with the spaces offering equipment, training, and a supporting community. The makerspace concept has also been adopted within many libraries to provide a common site for making in a community. The equipment in most library makerspaces is generally quite limited, but the concept of providing access and community is the same as that of the more fully equipped community-based makerspaces.

The corporate world has also noticed the maker phenomena and responded with privately owned and operated facilities along three dimensions (8). Commercial makerspaces, such as the national chain TechShop, have been established to allow access and training to customers who purchase a membership. Industrial makerspaces, including GE FirstBuild (Louisville, KY), Autodesk Pier 9 Workshop (San Francisco, CA), Autodesk BUILD Space (Boston, MA), and MIT Lincoln Laboratory Beaver Works Center (Cambridge, MA) have been created to mimic the communal nature of the community-based spaces in corporate settings. Each has a mission analogous to the community-based makerspaces, such as "creating a socially engaged community of home enthusiasts, designers, engineers, and makers who will share ideas, try them out, and build real products," and "house a state-of-the-art digital fabrication workshop to explore the interface between software and hardware (to) create an environment that fosters experimentation and learning" (9,10). Commercial makerspaces that cater to entrepreneurs, such as The Grommet (Somerville, MA), NextFab Studios (Philadelphia, PA), and the Columbus Idea Foundry (Columbus, OH), have also been created to help entrepreneurs develop and launch products from a facility that provides both equipment and a supportive community.

A review of the history (as referenced in this section) and the present state of the maker movement illustrates attributes common to makerspaces and their communities:

- In addition to access to machinery, the facilities provide access to equipment training and maker-related workshops, often taught using peer-to-peer instruction.
- Maker communities are supportive of one another, willingly collaborate, and originate from diverse backgrounds.
- Programs at makerspaces support project-driven discovery and just-in-time learning of new skills.
- Self-directed, active members design and direct their own learning and making trajectories.
- Maker communities need to be self-sustaining, innovative, and dynamic.
- Growth is key to sustainment, and communities thrive when they are inviting and welcoming for new members.

It is proposed that effective higher education maker communities share many of these same attributes.

HIGHER EDUCATION AND THE MAKERSPACE CULTURE

Within academia, the concept of making is a natural extension of many existing components of the curriculum and university infrastructure, including an increased emphasis on developing design skills, project-based learning, and student engagement within the classroom. The traditional infrastructure of teaching labs, computer centers and machine shops provide a foundation for engineering programs to apply best practices from such programs to create facilities that have a wider purpose (11,12,13). This section explains how a higher education makerspace differs from traditional facilities and describes the variety of programs that may be housed in an academic makerspace. The activities within a higher education makerspace are generally well aligned with the concepts of active learning, project-based learning, and incorporating design experiences throughout the curriculum that are promoted as alternatives to standard lectures and labs. This alignment has aided the rapid acceptance of higher education makerspaces as significant contributors to a university's mission.

The differentiation between higher education makerspaces and existing non-classroom facilities for design, fabrication and assembly is the recognition that the "makerspace" is not just a facility but is also a community of committed members (instructors, staff, and users) that have responsibilities and privileges associated with the space. In addition to the facility and people, higher education makerspaces also include the range of programs that unite, educate, and promote the community. Similar to the previously reported examples, the combination of facilities, people, and programs creates the maker culture that is critical to learning within a higher education makerspace.

Another significant aspect of higher education makerspaces is their extensive reach in terms of use. Higher education makerspaces are commonly used to support design classes, as well a large number of other activities. The design classes themselves need not be aligned on a single academic discipline, but instead be interdisciplinary, multi-disciplinary, or discipline-agnostic. An example of a discipline-agnostic course would be a problem solving class that teaches design theory and fabrication skills that can be applied to generic, non-discipline specific problems. Other activities hosted in a higher education makerspace can include supporting design-focused engineering student organizations which fabricate race cars, rockets, autonomous vehicles, robots, and genetic engineered solutions, to list a few. The uses also include personal projects, summer programs, outreach activities, and entrepreneurial pursuits centered on creating and building.

The thriving collection of uses produces a diverse group of users. A culture of inclusion, openness, and collaboration is a characteristic of many higher education makerspaces, and a rich collection of activities provides a range of skills that, because of the communal structure, can be shared and applied to other projects. Thriving higher education makerspaces host workshops and training sessions where peers teach one another about design, fabrication, and technology. This form of peer-to-peer instruction is unique to higher education makerspaces as compared to the authority-delivered instructional methods used in most engineering labs, machine shops, and computer centers. The makerspace culture leverages the skills and willingness of members to share their knowledge with others.

As earlier stated, higher education makerspaces include the facilities, people, and programs conducted within the facility. Figure 1 illustrates a range of programs that may be offered within a makerspace. Here, informal activities typically involved members of the makerspace community interacting directly with each other, with little oversight or direction provided by the makerspace staff. The formal activities, such as credit awarding classes taught by faculty members, professionally aided summer design internships, and presentations by visiting experts, are activities in essence provided by others to the maker community. This suite of activities, similar to those conducted by the community-based and corporate programs previously discussed, generate energy within the community, are a mechanism to constantly attract new members, and increase design skills of existing members. In addition, these create energy within the space, keeping them innovative and dynamic. Because of the range of activities, the spaces energize the users.

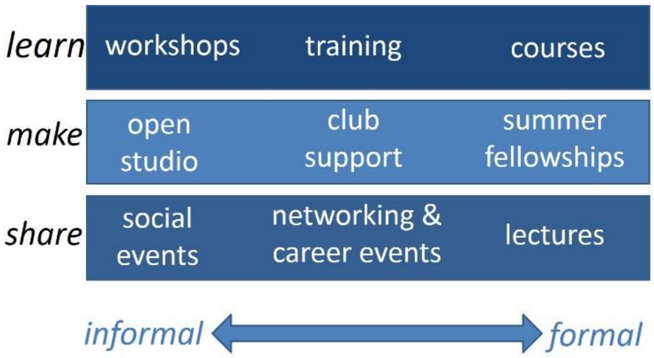

Fig. 1 Programs offered within a higher education makerspace.

While much of the activity within a higher education makerspace is created by the members, it is important to realize that a support staff is needed to keep makerspaces operating. The staff must, first and foremost, be effective educators who serve as the cultural leaders for the maker community. The staff, with talents ranging from those needed to teach courses to those needed to keep equipment operating, must have strong interpersonal, technical, and communication skills. This is essential as the staff develop the tone of the higher education makerspace.

As noted in the historical review, thriving makerspaces are ones that welcome new members and become a place where people want to be. Staff who are not student-centered and who do not promote working in a learning environment (including accepting the concept of failure as part of the learning experience) would not be ideal contributors to the makerspace culture.

IMPACT OF THE MAKERSPACE CULTURE ON MECHANICAL ENGINEERING

This section reviews the impact of academic makerspaces on mechanical engineering education using two institutional case studies. The focus is on curricular applications, detailing how the availability of higher education makerspaces benefit individual design classes, project-based engineering theory courses, and provide a mechanism to export design thinking and engineered results into the community at large. The two profiled institutions, and their associate makerspaces, are the U.S. Coast Guard Academy (Mechanical Engineering) and Yale University (School of Engineering & Applied Science).

Fig 2 Design Lab instructional area at the U.S. Coast Guard Academy.

The “Design Lab” in the Mechanical Engineering program at the U.S. Coast Guard Academy is a facility for instruction, design, fabrication, and assembly (Figure 2). Encompassing 1,200 square feet, the lab includes an instructional area and a studio set up for 10 teams to work independently (Figure 3).

Fig 3 Design Lab assembly area at the U.S. Coast Guard Academy.

Rapid prototyping equipment is provided in the space, with access to industrial machine tools in a more traditional machine shop setting (5,400 square feet) provided in an adjoining space. Access to data acquisition sensors and equipment is also provided in an adjoining (600 square feet) space. The space is open 24/7 and is accessible to students enrolled in courses based in the Design Lab.

These facilities primarily support the two-semester capstone design course (where the first semester addresses problem identification and design process management, while the second semester addresses fabricating, assembling, and testing the designed solution). In addition, the space supports an introduction to mechanical engineering course that exposes student to computer aided modelling and machining using a project-based scenario where individual students model and fabricate small air engines.

The lab also supports independent research projects and provides project space for designing, fabricating and applying mechanical and electromechanical systems within the following courses: Mechanisms, Machine Design, and Experimental Methods.

Fig 4 Open studio area at the Yale Center for Engineering Innovation and Design.

The "Yale Center for Engineering Innovation and Design" (CEID) is a 9,000 square foot facility housed in the School of Engineering & Applied Sciences that is available to all students, faculty, and research staff at Yale University. The CEID includes an instruction area, an open studio, meeting rooms, metal and wood workshops, and a wet-lab (Biosafety Level 1). The CEID has rapid-prototyping equipment (3D printers, laser cutter) and CNC mills/lathes/router, as well as electronics equipment and hand tools (Figure 4). The space is accessible 24/7 (with the machinery spaces accessible only when staff are on-site) and is used by 2,000 members of the Yale community. These members included undergraduate and graduate students from nearly every academic program at Yale (Figure 5).

The Yale CEID hosts approximately 10 design courses each year and is available for its members to use for course, club, research, entrepreneurial, and personal projects. A staff of 4.5 individuals (plus 7 student aides) support the center as course instructors, design guides, program planners, equipment trainers, and machinery maintainers. In addition to the courses, the CEID hosts weekly workshops on maker-centered topics (such as microprocessor programming, analog and digital circuits, computer aided design, and small engine dissection) as well as social activities (such as study breaks, movie nights, and an annual CEID Birthday Celebration). This range of activities has produced a large and collaborative community that promotes the maker culture on Yale's campus.

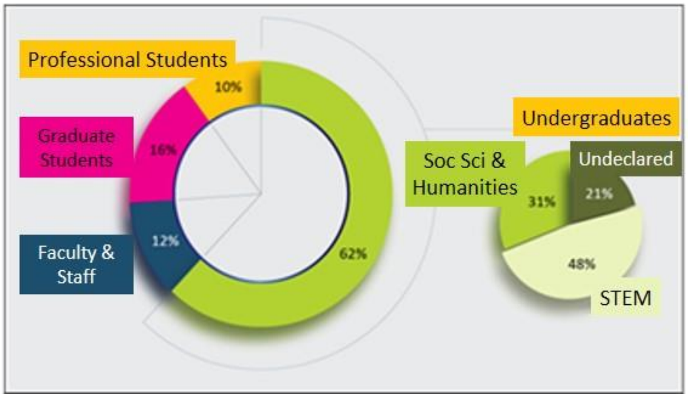

Fig 5 Demographics of the 2,000 members of the Yale Center for Engineering Innovation and Design.

A review of these two higher education makerspaces illustrates the impact of the maker culture on mechanical engineering education at each institution. The Design Lab at the U.S. Coast Guard Academy provides a central location that allows students to practice the design skills needed by a mechanical engineer. As the site is devoted to the mechanical engineering major, students benefit from training on fabrication equipment in this space (and the adjoining spaces) and then using the same equipment in a series of courses.

By the time the students enter the design, fabrication, and assembly stages of their capstone design projects, they have a set of skills that have been honed over a series of courses. While this skill enhancement occurs in other programs, it is accelerated by having students work in a common space for a series of courses. The Design Lab has also benefitted the program as a facility for students to work on design-test-build open-ended problems in other engineering fundamentals. As such the Design Lab has been a significant contributor to the program's "design across the curriculum" initiative.

The Yale CEID design courses span the biomedical, environmental, electrical, and mechanical engineering disciplines. Of note is that the CEID supports the Introduction to Engineering Innovation and Design course (for freshman) and the Mechanical Engineering: Process and Implementation capstone course. In addition to these two courses (anchoring each end of the curriculum), the CEID hosts design courses open to all students (with the required preparation) without regard to their academic major or year.

The mechanical engineering related courses include Appropriate Technology for the Developing World, Design of Medical Instruments, Musical Acoustics and Musical Instrument Design, and Product Development & Entrepreneurship. Of significance here is that the majority of these courses were added to the curriculum after the CEID was created. This demonstrates how the existence of a strong maker culture can lead to the development of a continuum of design courses.

It is also noted that the engineering accrediting board favors a spectrum of design experiences, spanning the four years of a student's undergraduate program. Thus higher education makerspaces have the potential to help achieve and maintain program accreditation. This progressive model of design courses, including introductory, intermediate, and capstone design courses can be more easily established and supported when an institution has an academic makerspace available.

Beyond these internally focused results it is essential to note that experiences at both institutions support the notion that higher education makerspaces also help export design skills into the broader community. For example, rapid manufacturing skills and equipment originating from the U.S. Coast Guard Academy Design Lab were deployed on a U.S. Coast Guard icebreaker. This technology was used while the ship was on patrol in the Arctic to fabricate 3D parts that would not have otherwise been able to be reproduced in this remote area.

Exportation of design skills gained at the Yale Center for Engineering Innovation and Design has fueled a number of start-up businesses where graduates used the prototypes developed as students to launch companies. Beyond the value of fabrication skills, both of these examples highlight the value of the maker culture: individuals who learn from one another and then share that knowledge with others. As with the previous examples, these results are not limited to individuals from higher education makerspaces, but it is suggested that their makerspace experiences accelerated their abilities to make contributions in each case.

COMMON PRACTICES WITHIN MAKERSPACE COMMUNITIES

A review of makerspaces in general and higher education makerspaces in particular provides insights on common practices within the makerspace communities. The first commonality is the awareness that the space itself (the physical structure and the fabrication equipment) is a component of a larger ecosystem that includes the community that staffs and uses the facility. Also significant are the programs established by members of the community to learn new skills and establish social connections. Collectively the members of a makerspace community create a unique culture that is supportive, collaborative, and inviting.

This culture is important not only to sustain the makerspace community, but also to keep it safe. Effective makerspace communities promote a culture of safety where the community provides safety training and reinforces safe practices. A healthy safety culture encourages community-based practices, enforces personal accountability, and promotes dialog (about safety) among community members. The members themselves recognize that safety is part of the maker culture. Safety awareness extends beyond the equipment and tools used to create designs and includes the engineered systems that are created using the tools and equipment. Safety reviews are commonly a part of every project.

The concept of ownership is fundamental to makerspaces. Members of a makerspace community understand the need to contribute to the community in order to sustain it. This understanding manifests itself in the conduct of individual members in the makerspace where they are responsible for all aspects of their design process, including obtaining supplies, returning tools to their designed spaces, using equipment in a safe manner, and leaving the space clean and ready to be used by another member at the end of their work session. In addition to these operational characteristics, thriving communities have members who willingly share their skills and experiences with others in spontaneous individual instruction sessions and more formally organized workshops. The community learns from one another.

Diversity benefits the problem solution process by introducing new methods of thinking. Thriving higher education makerspaces include project teams with members from a variety of academic disciplines. Since makerspace members have a culture of helping each other, it is not uncommon to have a project benefit from insights that originated in completely different disciplines.

As one example an active research project on fMRI research of birds benefitted from a CEID affiliation that led to the design and fabrication of a 3D-printed devise to hold the bird's head still while the medical image was collected. Such a development may not have been as quick to materialize if the project team was limited to medical imaging specialists. The openness and collaborative nature of makerspace members promotes this form of shared discovery.

It may be generalized that most non-academic makerspaces focus on product development, and the accumulation of individual skills to design, fabricate, and develop those products. It is proposed that the focus of higher education makerspaces needs to be on people development, where the skills to design, fabricate, and develop products become one part of an individual's problem-solving skills. This distinction is essential for higher education makerspaces, as it emphasizes the role of this activity as a component of an individual's development.

OBSERVATIONS

Higher education makerspaces are a new and exciting component on college campuses, contributing in many ways to the educational experience and professional development of makerspace users. Three observations are presented to understand and expand the impact of higher education makerspaces on engineering education.

As emphasized in this paper the facility, community, and activities associated with a higher education makerspace establish a culture for creating and making. The resulting culture is defined by each part of the system (the facility, the community, and the programs) and it is the resulting culture that produces direct and indirect effects on members of the local making community. Regarding the direct effects on engineering education, it has been reported that a strong making culture increases students' abilities to solve open-ended design problems and enhances design skills (14, 15). The indirect effects on engineering education include an increase in student confidence to solve engineering challenges and an appreciation of collaboration as a problem solution strategy (15). In a variety of forms, the maker community has the potential to impact engineering education at the home institution.

Many models for higher education makerspaces exist. For example, spaces originate from students, faculty, administrators, or hybrid groups and this foundation may influence the operation and impact of the space on its members (14). Further, higher education makerspaces have unique uses on each campus with some devoted to course support and others primarily used for engineering clubs and personal projects, while noting some spaces support all uses (16). The users of each makerspace are also unique to each organization where some spaces are restricted to individuals in a specific course or discipline, while other spaces have an open membership model. It is essential to note that a single best practice model does not exist for higher education makerspaces, but rather the space and the community must be developed to meet the specific institution's goals.

With the exception of a few institutions, most higher education makerspaces are less than five years old. Further, most of the higher education makerspaces were created as a result of the efforts of individuals who surveyed existing spaces and combined these insights with the needs and desires on their home campuses to create the local facility. Given this new and principally organic growth, there is a strong need for studying higher education makerspaces to better understand their value in the education system, increase their effectiveness to improve engineering education, and document best practices. Such studies can be used locally to improve existing higher education makerspaces and globally to provide direction to institutions that will construct future higher education maker spaces. While this paper can contribute to that effort, professional society leadership is needed to accelerate this study process and the associated dissemination of information.

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